ENERGY-EFFICIENCY AND COMFORT CONDITIONS THROUGH THERMAL MASS IN PASSIVE SOLAR BUILDINGS AT EQUATORIAL HIGH ALTITUDES

By

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By

DAVID MWALE OGOLI

Dedicated to Roy and Sharon

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Abstract of Dissertation Presented to the Graduate School
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By

David Mwale Ogoli

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Chairman: Professor Gary W. Siebein
Major Department: Architecture

This dissertation is based on the philosophy that architectural design should not just be a function of aesthetics, but also of energy-efficiency, advanced technologies and passive solar strategies. A lot of published literature is silent regarding buildings in equatorial highland regions. This dissertation is part of the body of knowledge that attempts to provide a study of energy in buildings using thermal mass.

The objectives were to establish (1) effect of equatorial high-altitude climate on thermal mass, (2) effect of thermal mass on moderating indoor temperatures, (3) effect of thermal mass in reducing heating and cooling energy, and (4) the amount of time lag and decrement factor of thermal mass.

Evidence to analyze the effect of thermal mass issues came from three sources. First, experimental physical models involving four houses were parametrically conducted in Nairobi, Kenya. Second, energy computations were made using variations in thermal mass for determining annual energy usage and costs. Third, the data gathered were observed, evaluated, and compared with currently published research.

The findings showed that: (1) Equatorial high-altitude climates that have diurnal temperature ranging about 10-15°C allow thermal mass to moderate indoor temperatures; (2) Several equations were established that indicate that indoor mean radiant temperatures can be predicted from outdoor temperatures; (3) Thermal mass can reduce annual energy for heating and cooling by about 71%; (4) Time lag and decrement of 200mm thick stone and concrete thermal mass can be predicted by a new formula; (5) All windows on a building should be shaded. East and west windows when shaded save 51% of the cooling energy. North and south windows when fully shaded account for a further 26% of the cooling energy; (6) Insulation on the outside of a wall reduces energy use by about 19.6% below the levels with insulation on the inside.

The basic premise of this dissertation is that decisions that affect a building's use regarding thermal mass occur during early design stages. The intention is to present new knowledge to architects regarding the use of thermal mass in equatorial high altitude climates for energy-efficiency through passive solar strategies.

CHAPTER 1
INTRODUCTION

Since time immemorial humans have always sought shelters that offer indoor comfort from the vagaries of outdoor elements. Indoor climate is influenced by prevailing outdoor conditions. *The Energy Design Handbook*, edited by Watson,[1] was based on the thesis that architecture was "born of climate, energy and environment." A basic concept of energy design is the view that a building is a climate-responsive environmental system. Depending on location, season, use, occupancy pattern and lifestyle, buildings may be heated, ventilated, air conditioned and refrigerated to maintain indoor comfort (ASHRAE,[2] 1997, pp. 16.1).

This process takes up large amounts of energy, and, ASHRAE recognizes "the effect of its technology on the environment and natural resources to protect the welfare of posterity."[3] Residential and commercial buildings account for 20% of the total primary energy in the USA[4] and 40-50% in Europe.[5,6,7] In developing countries, the picture is more severe. For instance in Kenya, rural households make up about 80% of the population and they use 59% of the total energy in the sector.[8]

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[1] Watson, Donald (ed). 1993. *The Energy Design Handbook*. Washington, DC: AIA Press, The American Institute of Architects.

[2] The American Society of Heating Refrigerating, and Air-conditioning Engineers Inc. (ASHRAE), Atlanta, Georgia, is a professional organization of Engineers and allied professionals. It draws its membership from USA and other countries. It conducts basic research, and publishes handbooks and industry standards for the advancement of the knowledge of heating, ventilating and air conditioning (HVAC) of buildings. Based on authoritative research and assembled with great care, ASHRAE standards are accepted by many regulatory bodies locally and internationally.

[3] ASHRAE. 1990. *Energy position statement* (June). American Society of Heating Refrigerating, and Air-conditioning Engineers Inc. (ASHRAE), Atlanta, GA.

[4] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition)*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. See Figure 13 pp. 16.5.

[5] CIBSE: Chartered Institution of Building Services Engineers. 1998. *Energy Efficiency in Buildings: CIBSE Guide*, pp. 1-1. London: Chartered Institution of Building Services Engineers.

The use of heating, ventilating and air-conditioning (HVAC) systems have risen in recent years (Santamouris and Asimakopolous, 1996, pp. 12; Stein and Reynolds, 2000, pp. 9-12; Hinrichs, 1996, pp. 6), at the rate of almost 10% per year in USA. Today, two thirds of all households have some form of air conditioning (40% have central air), while 83% of all commercial space is air-conditioned.[9] In southeastern USA it is more serious. In a typical Florida residential power bill 49.5% is required for space heating and cooling. Water heating accounts for 22.9% of the energy expenses. Cooking, lighting and appliances and other miscellaneous sources use the remaining 27.5%.[10] Chapter 34 of the 1999 ASHRAE *Handbook of Applications* outlines different analysis techniques that may be used to select an optimum system for energy management currently adopted in Kenya.

ASHRAE acknowledges "the energy requirements and fuel consumption of HVAC systems have a direct impact on the cost of operating a building and an indirect impact on the environment."[11] A primary objective of building energy analysis is economic – to determine the most cost-effective method among available options. Many

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[6] Santamouris, M., A. Argiriou, E. Dascalaki, C. A. Balaris and A. Gaglia. 1994. Energy characteristics and savings potential in office buildings, in *Solar Energy* vol. 52 pp. 59-66. Amsterdam: Elsevier Science Limited.

[7] Lewis, J. Owen. 2000. Developing a low energy architecture for Europe in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 10-15. James & James (Science Publishers) Ltd.

[8] Hankin, M. 1987. *Renewable Energy in Kenya*. Nairobi: Creative Motives, pp. 2.

[9] Hinrichs, Roger, A. 1996. *Energy: Its use and the environment*. New York: Saunders College Publishing pp. 137.

[10] Florida Solar Energy Center (FSEC). 1992. Manual entitled: *Energy-efficient Florida Home Building* FSEC-GP-33-88 by Veira, Robin K., Kenneth G. Sheinkopf and Jeffrey K. Sonne at Florida Solar Energy Center (FSEC) Cape Canaveral, FL. pp. 2-1.

[11] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition)*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. pp. 30.1.

developing countries cannot afford the rising costs of fossil fuels, and therefore, have to develop renewable energy sources. Consequently, interest in the use of natural energies as substitutes for conventional fuels has been renewed and intensified. The local climate, type of building, schedule of usage, equipment, appliances and the lifestyles of the users influence energy consumption in buildings.

Buildings account for 40% of the materials and about one third of the energy consumed by the world economy.[12] The world acknowledges that environmental problems are associated with CFC refrigerants in HVAC systems that are causing ozone depletion. Recent studies (ASHRAE,[13] Baker,[14] Santamouris,[15] UNCHS,[16] Dennison[17]) have shown that problems with indoor air quality and illness occur more frequently in deep-plan buildings with air-conditioning than in those without air conditioning. "Sick building syndrome," more commonly called "building-related illness," has focused attention on the need to evaluate how buildings are designed, ventilated and maintained.[18,19] Watson,[20] Santamouris,[21] Givoni[22] and Goulding *et al.*[23] suggested a framework of considering passive and low energy architecture in the context of energy conservation as prevention of excess heat, temperature modulation[24] and heat dissipation through ventilation, a concept summarized in the figure below. Thermal mass is commonly used in two broad strategies: passive cooling and passive heating.

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[12] Rees, William, E. 1999. The built-environment and the ecosphere: a global perspective. *Building Research & Information*, (1999) 27 (4/5), 206-220. London: E & FN Spon.

[13] Ibid. pp. 9.5.

[14] Baker, N. V. 2000. We are all outdoor animals in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 553-555. James & James (Science Publishers) Ltd.

[15] Santamouris, M. and D. Asimakopolous (ed). 1996. *Passive Cooling of Buildings.* London: James & James (Science Publishers) Ltd. pp. 37.

[16] UNCHS: United Nations Conference of Human Settlements (Habitat). 2000. *Building Sustainable Cities* by Rainer Norberg and *Conflicts Between the Construction Industry and the Environment* by Baris Der-Petrossian at http://www.unchs.org/unchs/english/hdv5n2/intro.htm.

[17] Dennison, Peter, J. 1994. An Examination and Analysis of Sick Building Syndrome in Selected Libraries of Great Britain. Master's Thesis at Loughborough University, UK.

[18] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition).* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. pp. 13.5.

[19] Fitch, James Marston with William Bobenhausen. 1999. *American Building: The Environmental forces that shape it.* New York: Oxford University Press pp. 90.

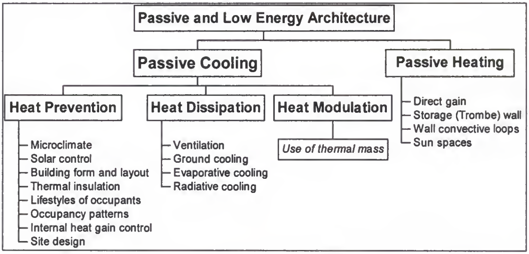

Figure 1: Strategies of passive and low energy architecture

A recent study by Cook[25] traced the evolution of modern office architecture in the USA and showed that it was generally associated with air conditioning, artificial lighting and the emergence of the high-rise typology, the skyscraper. Cook observed:

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[20] Watson, Donald (ed). 1993. *The Energy Design Handbook*. Washington, DC: AIA Press, The American Institute of Architects.

[21] Santamouris, M. and D. Asimakopolous (ed). 1996. pp. 6.

[22] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. Van Nostrand Reinhold, New York, NY. pp. 149.

[23] Goulding, J. R., J. Owen Lewis and T. C. Steemers (eds). 1992. *Energy in Architecture, The European Solar Handbook*, Commission of the European Communities, Brussels.

[24] "Modulation" means the ability of the building to reduce, regulate or adjust the amplitude of daily indoor temperature against daily outdoor temperature swings. The thermal mass of a building (typically contained in walls, floors and partitions, constructed of material with high heat capacity) absorbs heat during the day and regulates the magnitude of indoor temperature swings, reduces peak cooling load and transfers part of the absorbed heat into the night hours (Santamouris and Asimakopolous, 1996. pp. 8).

[25] Cook, Jeffrey. 2000. Evolution of American office architecture to 1950: Pollution vs. passive strategies to design the work environment in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 16-21. James & James (Science Publishers) Ltd.

> Essentially, it took over a half a century, up to 1950 for true air conditioning to shift the architectural paradigm and to free exterior form from the restraints of daylighting and natural ventilation. Thereafter, it took less than a quarter century to rediscover passively based architectural design.

These shifts and the succession in architectural styles (International style to Post-modernism) offer important lessons for developing countries. Daylighting and natural ventilation required high floor-to-ceiling heights and high building heights. Radovic[26] highlighted environmental issues for offices. For passive solar strategies to be effective, they should be evaluated continually throughout the design process. To use the words of Balcomb, *et al.* (1996, pp. 37):

> This is an iterative process – design, adjust the model, review, design, adjust the building description, evaluate, design, adjust the building description, review, etc. Each step along the way represents a different design scheme.[27]

The Commission of European Communities (CEC)[28] said that "Architecture is a process" and this idea is implied in a model[29] shown below in Figure 2. The idea conveyed by this method is that the iterative nature of architecture should move forward an backwards to test and re-test applicable solutions. This is true for establishing passive solar strategies that are climate-responsive and appropriate for a given region.

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[26] Radovic, Darko. 2000. Green office building: Environmental issues and themes as seen by architects in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 38-41. James & James (Science Publishers) Ltd.

[27] Balcomb, J. Douglas. 1996. *Designing low-energy buildings: Passive solar strategies and Energy-10 Software.* Developed in collaboration with Passive Solar Industries Council, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and US Department of Energy (DOE) pp. 37.

[28] CEC: Commission of European Communities. 1990. *Passive solar energy as a fuel – 1990-2010.* Executive Summary, Commission of European Communities, DGXII, pp. 29.

[29] Ogoli, David Mwale. 2000. An assessment method for the performance of passive solar buildings at equatorial high altitudes in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge,*

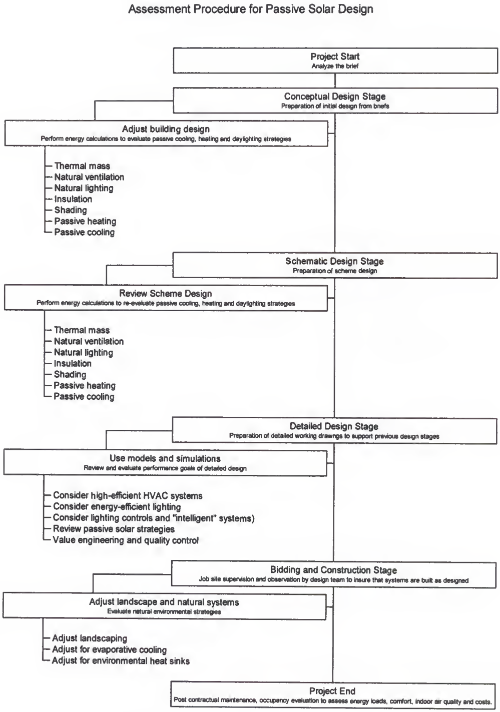
Assessment Procedure for Passive Solar Design
Project Start
Analyze the brief
Conceptual Design Stage
Preparation of initial design from briefs
Adjust building design
Perform energy calculations to evaluate passive cooling, heating and daylighting strategies
Thermal mass
Natural ventilation
Natural lighting
Insulation
Shading
Passive heating
Passive cooling
Schematic Design Stage
Preparation of scheme design
Review Scheme Design
Perform energy calculations to re-evaluate passive cooling, heating and daylighting strategies
Thermal mass
Natural ventilation
Natural lighting
Insulation
Shading
Passive heating
Passive cooling
Detailed Design Stage
Preparation of detailed working drawings to support previous design stages
Use models and simulations
Review and evaluate performance goals of detailed design
Consider high-efficient HVAC systems
Consider energy-efficient lighting
Consider lighting controls and "intelligent" systems)
Review passive solar strategies
Value engineering and quality control
Bidding and Construction Stage
Job site supervision and observation by design team to insure that systems are built as designed
Adjust landscape and natural systems
Evaluate natural environmental strategies
Adjust landscaping
Adjust for evaporative cooling
Adjust for environmental heat sinks
Project End
Post contractual maintenance, occupancy evaluation to assess energy loads, comfort, indoor air quality and costs.

Figure 2: Assessing passive solar design

UK (July 2000) by Koen Steemers and Simos Yannas (eds) pp. 827-828. James & James (Science Publishers) Ltd.

Goals and Objectives

The goal of this study is to establish the benefits and limitations[30] of thermal mass in passive solar buildings at equatorial high-altitudes. The objectives were to establish:

1. Effect of equatorial high-altitude climate on thermal mass.
2. Effect of thermal mass on modulation or moderation[31] of internal thermal conditions using a series of experimental test houses.
3. Effect of thermal mass in reducing heating and cooling loads for the attainment of thermal comfort that requires (a) minimum use of conventional energy, is (b) climate-sensitive and (c) environmentally conscious in equatorial high altitudes.
4. The amount of time lag and decrement factor of thermal mass.

The main theme for this research is to study the method of energy-efficiency[32] and comfort conditions in buildings using thermal mass in moderating internal temperature. Controlled temperature is a measure of the thermal comfort conditions in a building. It takes energy to maintain comfortable ambient temperatures. There is a

---

[30] There are some "limitations" of using thermal mass that have been observed in some climates (Balcomb, 1996, pp. 105). Thermal mass can reduce both the peak and total energy required during the following day (Braun, 1990; Andresen and Brandemuehl, 1992) but may not always be efficient. Even night ventilation and pre-cooling despite their advantages are known to have limitations (ASHRAE, 1999, pp. 33.18).

[31] "Modulation or moderation" is used to mean the ability of the building to reduce, regulate or adjust the amplitude of daily indoor temperature against daily outdoor temperature swings.

[32] Energy-efficiency is measured by the "energy-efficiency ratio" (EER), which is a ratio of the energy used to get auxiliary heating or cooling in a space to the net energy supplied from external sources.

$$\text{Energy-efficiency ratio (EER)} = \frac{\text{Auxiliary heating (or cooling) energy required}}{\text{Net Energy supplied from external sources}}$$

EER is similar to the ASHRAE coefficient of performance (COP) defined as the benefit of the refrigeration cycle (amount of heat removed) divided by the required energy input to operate the cycle, or

$$\text{Coefficient of performance (COP)} = \frac{\text{Useful refrigerating effect}}{\text{Net energy supplied from external sources}}$$

worldwide need to reduce the use of harmful systems[33] because of their impact on energy usage.[34] The "Earth Summit" held in Rio de Janeiro in June 1992 and the "Kyoto Protocol" held in Japan in December 1997 were efforts made to control adverse effects on the environment and climate change caused by large energy demand due to rapid human growth.[35] Passive cooling and heating systems are climate-conscious solutions to architectural design. This means that the size, capacity and energy input for supplementary HVAC systems can be designed to the optimal level[36].

The theme of this research arises out of the need to optimize energy use in buildings and to make intelligent use of the available resources to create a comfortable and healthy built environment. The human population is rapidly urbanizing, leading many observers to conclude that humans are leaving nature and the countryside behind.[37, 38] Up to 80% of the populations of high-income countries already live in cities and towns, and 25% of the human population consumes 80% of the world's economic

---

(ASHRAE, 1997, pp. 1.3)

[33] Reduction of harmful systems were the reason that the Rio Earth Summit was held in June 1992 where 118 heads of state stressed that one nation could longer do anything it wants with its environment without regard to the impact on other countries. They established goals to stabilize carbon dioxide and other green house gas emissions and set Agenda 21, an environmental action plan for the 21st century that covered sustainable development, etc.

[34] Hinrichs, Roger, A. 1996. *Energy: Its use and the environment*. New York: Saunders College Publishing pp. 25-28, 238-278.

[35] Worldwatch Paper 124, March 1995. Jane A. Peterson (ed). *Building Revolution: How Ecology and Health Concerns are Transforming Construction* by David Malin and Roodman and Nicholas Lenssen. Worldwatch Institute, 1776 Massachusetts Ave., NW Washington DC 20036. Also found at http://www.worldwatch.org/pubs/paper/124.html.

[36] The term "Optimal level" is used to denote the best and correct sizing HVAC system that complements the positive contribution of passive systems.

[37] Rees, William, E. 1999. The built-environment and the ecosphere: a global perspective. *Building Research & Information*, (1999) 27 (4/5), 206-220. London: E & FN Spon.

[38] Baker, N. V. 2000. We are all outdoor animals in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 553-555. James & James (Science Publishers) Ltd.

output.[39] In short, "half the people and three-quarters of the world's environmental problems reside in cities."[40] Cities have most buildings that are increasingly dependent on mechanically controlled indoor climates. Yet low-energy design is still not widely adopted (Yannas, 1994, pp. 23).

Large architectural design issues like building location, form, shape, orientation, landscaping, envelope, daylighting, and doors and windows can control the effects of solar radiation even when outdoor temperatures are too high or too low. A passive solar building balances all aspects of energy use (lighting, cooling, heating and ventilation) by focusing on whole building performance[41] (Balcomb, 1996, pp. 14). CEC[42] said:

> Passive solar design uses building form and fabric to admit, distribute and re-emit solar energy radiation, conduction and natural convection. Passive systems obtain solar energy from glazing (direct gain), thermal mass (indirect gain from solar energy, first absorbed by the thermal mass and then radiated or convected as heat), or a separate storage system (isolated gain, usually heat transferred from a thermal mass away from a thermal mass away from the main building.

A passive solar building should be economical yet inspire human intelligence.

Scope and Framework of the Study

The dissertation provides observations on the role of thermal mass and does not purport to answer every question regarding passive solar methods in general. The criteria used to comment on other methods are the degree to which they make thermal mass more effective in moderating indoor temperature against outdoor temperature swings.

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[39] WCED. 1987. *Our Common Future*. Report of the (UN) World Commission on Environment and Development, New York and Oxford: Oxford University Press.

[40] Rees, William E. 1997. Is "sustainable city" an oxymoron? *Local Environment*, 2 (2), 303-310. London: E & FN Spon.

[41] Whole building performance derives its meaning from the principle that the whole is the sum of its parts. For passive solar buildings it implies developing a design team early in the design process to develop the building shell, the lighting systems, mechanical systems of that building for energy-efficiency.

[42] CEC: Commission of European Communities. 1990. *Passive solar energy as a fuel – 1990-2010*. Executive Summary, Commission of European Communities, DGXII, pp. 10.

In general cases, most literature on architecture describes buildings in terms of culture, regional context, language, proportion, balance, rhythm, color, texture and experience.[43,44,45,46,47,48,49,50,51] Hersey (1988, pp. 1) asked the question "Why do we still use the classical orders?" and proceeded to discuss architectural elements from the Greeks and Romans. Norberg-Schulz (1965, pp. 113) saw a building envelope not merely as a set of two-dimensional exterior surfaces but as elements that perform certain functions: filters, connectors, barriers and switches. He introduced the concepts of filters, connectors, barriers and switches, and said:

> An opaque wall thus serves as a filter to heat and cold, and as a barrier to light. Doors and windows have the character of switches, because they can stop or connect at will. In general we define a 'connector' as a means to establish a direct physical connection, a 'filter' as a means to make the connection indirect (controlled), a 'switch' as a regulating connector, and a 'barrier' as a separating element."[52]

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[43] Fitch, James Marston with William Bobenhausen. 1999. *American Building: The Environmental forces that shape it.* New York: Oxford University Press pp. 4.

[44] Norberg-Schulz, Christian. 1965. *Intentions in Architecture.* Cambridge, Massachusetts: The MIT Press.

[45] Denyer S. 1978. *Traditional Architecture in Africa.* Lagos: Oxford University Press.

[46] Andersen, K. B. 1978. *African Traditional Architecture: A study of the housing and settlement patterns of rural Kenya.* Nairobi: Oxford University Press.

[47] Nnamdi, Elleh. 1996. *African Architecture.* New York: McGraw-Hill.

[48] Rapoport, A. 1969. *House Form and Culture.* London: Heinemann.

[49] Smith, E. Baldwin. 1938. *Egyptian Architecture as Cultural Expression.* New York: Appleton-Century Co.

[50] Hersey, Goerge. 1988. *The Lost Meaning in Classical Architecture: Speculations on Ornament from Vitruvius to Venturi.* Cambridge, Massachusetts: The MIT Press.

[51] Semper, Gottfried. 1980. *The Four Elements of Architecture and Other Writings.* Cambridge, England: Cambridge University Press.

[52] Norberg-Schulz, Christian. 1965. *Intentions in Architecture.* Cambridge, Massachusetts: The MIT Press, pp. 113.

These concepts can be used to describe all possible conditions of physical control and experience in a building. Experience is based on stimuli from the environment: acoustic, lighting, thermal and olfactory stimuli. This dissertation limits itself to the thermal environment. The framework of this study used the concept that Fitch with Bobenhausen[53] referred to as *submerged* in the experience and not just *exposed* to it. They compared the experience and appreciation of architecture and that of other art forms. The relationship one has in viewing a painting or listening to a concert is of a simple *exposure*. The fundamental thesis of this study was the total experience, that is, *submerged* and *exposed* to the thermal environment. While this may be hard to assess in simple terms, it will be taken to mean the ability of an occupant of a room to experience complete thermal comfort in an environment because "in spite of the extra physiological effort required to adjust to thermal stimuli, people definitely seem to enjoy a range of temperatures. Indeed they frequently seek an extreme thermal environment for recreation or vacation; to beaches in summer to bake in the sun and travel great distances in the winter to ski on frosty mountain tops." (Heschong, 1979, pp. 21).[54] This moves toward a situation where human senses receive physical thermal stimuli with fluctuating interior temperatures and eliminate "thermal boredom,"[55,56] first suggested by McIntyre (1980).[57]

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[53] Fitch, James Marston with William Bobenhausen. 1999. *American Building: The Environmental forces that shape it.* New York: Oxford University Press pp. 4.

[54] Heschong, Lisa. 1979. *Thermal Delight in Architecture.* Cambridge, Massachusetts: The MIT Press.

[55] Kwok, Alison G. 2000. Are you thermally bored? In *SBSE News* Spring 2000 Bruce Haglund (ed). Society of Building Science Educators. http://www.polaris.net/~sbse/web/

[56] Kwok, Alison G. 2000. Thermal Boredom in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 640-641. James & James (Science Publishers) Ltd.

[57] McIntyre, D. A. 1980b. *Indoor Climate.* London: Applied Science Publishers.

Research Method

Evidence to analyze the effect of thermal mass issues came from three basic sources:

1. Observed data from four experimental test houses conducted in Nairobi, Kenya. These new data are the basis for comparison with other studies.
2. Presentation and comparison with recent research and observed data. It tested some control algorithms established in previous studies.
3. Comparison of annual energy use in a standard "conventional" building and a passive solar building with high thermal mass was determined by using Givoni (1976, pp. 414-450), *Energy-10, QUICK-II* and ASHRAE Thermal Comfort Tool.

Item 3 (above) compared two houses for a middle-income earner. The standard "conventional" building had minimum energy-saving features while the passive solar building has high thermal mass with low-cost energy-saving passive solar features.

For this study, inductive reasoning[58] was used to draw conclusions. It led to other methods also. There are two main methods used in thermal comfort research that have dominated most recent work: the climate-chamber (physical model) and field study (Humphreys, 1992, pp. 8).[59] Based on observed data from these two methods, a third method is evolving steadily: the computer model.[60,61,62,63,64,65,66,67] A physical model is a controlled experimental environment in which subjects or materials are tested to provide data for analysis. The field study is an observation in a "normal working" environment accompanied with measurements of that environment. Some computational methods are simplified and require few inputs to perform an analysis (*Energy-10* or *QUICK-II*), while others are quite advanced and require a great amount of input (ESP and TRNSYS). This third model is growing rapidly as computing technology improves.

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[58] Inductive reasoning is based on the term "induction" is defined as the process of discovering explanations for a set of particular facts. Induction is a bringing forward of separate facts or instances so as to prove a general statement. Induction reasoning is where particular facts lead to a general conclusion. George Gale in his book *The Theory of Science* said: "in deductive arguments, conclusions follow from the premises; inductive argument extends our knowledge but only on a certain rather strong assumptions" (Gale, 1992, pp. 27-28).

[59] Humphreys, Reverend Michael A. 1992. Thermal comfort in the context of energy conservation found in *Energy-efficient building* edited by Susan Roaf and Mary Hancock. New York: John Wiley & Sons. pp. 3-13.

This research looks at some current thermal comfort standards,[68] mainly ASHRAE Standard 55 and ISO Standard 7730, and their effects on people. The definition of "standards" raises the inherent problems of interpretation of such standards. For example, the "distinction of 'winter' and 'summer' mean different things in different

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[60] ECE: Economic Commission for Europe, Geneva. 1991. *Energy efficient design: a guide to energy efficiency and solar applications in building design.* ECE Energy series No. 9. New York: United Nations.

[61] Balcomb, J. Douglas. 1996. *Designing low-energy buildings: Passive solar strategies and Energy-10 Software*. Developed in collaboration with Passive Solar Industries Council, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and US Department of Energy (DOE).

[62] Santamouris, M. and D. Asimakopolous (ed). 1996. *Passive Cooling of Buildings.* London: James & James (Science Publishers) Ltd. pp. 158.

[63] Matthews, E. and P. Richards. 1989. A tool for predicting hourly air temperatures and sensible load in buildings at sketch design stage. *Energy and Buildings* 14 (1989) 61-80. Amsterdam: Elsevier Science Limited.

[64] Athienitis, Andreas K. 1988. A predictive control algorithm for massive buildings. *ASHRAE Transactions*, Vol. 94, No. 2, pp. 1050-1067. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[65] Balaras, C.A. 1996. The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and Buildings*, 24 (1996) 1-10. Amsterdam: Elsevier Science Limited.

[66] Clarke, J. 1985. *Energy simulation in Building Design*. Bristol, UK: Adam Hilger.

[67] Klein, S. 1988. TRNSYS – Transient system simulation program. *Engineering Experiment Station Report 38-12*. University of Wisconsin, Madison.

[68] A thermal comfort standard specifies thermal environmental conditions acceptable for healthy people at atmospheric pressure equivalent to altitudes up to 3,000 m (10,000 ft) in indoor spaces designed for human occupancy for periods not less than 15 minutes. This standard does not address such non-thermal environment factors such as air quality, acoustics, and illumination nor other physical, chemical, or biological space contaminants that may affect comfort or health (ASHRAE, 1992, pp. 3)

places. Winter in New York is different from winter in New Delhi or New Zealand."[69] Most equatorial regions have one long season marked by two rainy parts. This explains why, from region to region, temperature or thermal comfort standards are being established.[70,71,72,73,74,75,76] The dissertation questions why there should be the same comfort zone universally; in fact many studies[77,78,79] show it is not possible. Regarding the adaptive approach to different comfort standards, Humphreys[80] said:

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[69] Humphreys, Reverend M. A. 1995. Thermal comfort temperatures and the habits of hobbits: Comfort temperatures and climate. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 3-13.

[70] Sharples, Steve and Shahin Heidari. 2000. A thermal comfort survey of courtyard housing in Iran in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 224-228. James & James (Science Publishers) Ltd.

[71] Sharples, Steve and Albert Malama. 1997. A thermal comfort field survey in the cool season of Zambia. *Building and Environment*, Vol. 32, No. 3, pp. 237 – 243, 1997. Amsterdam: Elsevier Science Limited.

[72] Ahmed, Z. N. 1995. Temperature standards for the tropics? *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 31-39.

[73] Jokl, Miloslav V. 1995. New thermal comfort standards of the Czech Republic. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 40-49.

[74] Busch, John F. 1995. Thermal comfort in Thai air conditioned and naturally ventilated offices. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 114-121.

[75] De Dear, Richard J. 1995. Thermal comfort in air conditioned office buildings in the tropics. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 122-136.

[76] Nicol, J. Fergus. 1995. Thermal comfort standards in Pakistan. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 149-156.

[77] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design.* New York: Van Nostrand Reinhold, pp. 35-36.

[78] Humphreys, Reverend Michael A. 1996. Thermal comfort temperatures world-wide – The current position. *Renewable Energy*, Vol. 8 Issues 1-5 May 1996, pp139-144. Amsterdam: Elsevier Science Limited.

[79] Parsons, K. C. 1995. ISO Standards and thermal comfort: Recent developments. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 97-105.

[80] Humphreys, Reverend M. A. 1995. Thermal comfort temperatures and the habits of hobbits: Comfort temperatures and climate. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century.* Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 3-13.

> The Adaptive approach suggests that to some extent comfort standards have the nature of self-fulfilling prophecy. If a building is set regularly at, say, 22° C, the occupants will choose their clothing so that they are comfortable at that temperature. If enough buildings are controlled at this temperature, it becomes a norm for that society at that period of its history, and anything different is regarded as "uncomfortable," even though another generation might have preferred to wear more clothing and have cooler rooms, or to wear less clothing and have warmer rooms. So thermally comfortable temperatures are socially and historically conditioned.

A study[81] was carried to field-validate ASHRAE *Standard-55* comfort zone in a tropical setting using a standardized questionnaire and laboratory-grade instrumentation. It found that thermal "neutrality"[82] was approximately 1°C warmer than most acceptable temperature (calculated at 23.5°C). While ASHRAE and ISO Standards are used widely around the world, HVAC engineers usually have reservations when applying them to other climates. ASHRAE *Standard 55* was based on climate-chamber experiments using North American and European university students in mid-latitude climatic zones. Some studies question the relevance of using climate-chamber subjects for "real" people in real life situations in the tropics.[83,84,85] After acknowledging the fact that there is an apparent discrepancy between subjective assessments of comfort in field studies and the comfort criteria adopted by ISO 7730 and ASHRAE *Standard 55* based on the work of Fanger, the European Community established the PASCOOL task force to study it further.[86] Before 1995, most countries in Europe used ISO Standard 7730 unmodified.

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[81] De Dear, Richard J. 1995. Thermal comfort in air conditioned office buildings in the tropics. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century*. Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 122-136.

[82] Thermal neutrality is a term that refers to preferred temperature for most people; it is a temperature value where at least 80% of the occupants of a room find it acceptable.

[83] Rohles, F. H. 1978. The empirical approach to thermal comfort. *ASHRAE Transactions*, Vol. 84 (1) pp. 725-732. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[84] McIntyre, D. A. 1982. Climate chamber – reductio ad absurdum? *Energy and Buildings* 5 (1982) 89-96. Amsterdam: Elsevier Science Limited.

[85] Prins, G. 1992. Reply to comments on "On Condis and Coolth" *Energy and Buildings* 18 (1992) 267-268. Amsterdam: Elsevier Science Limited.

Technology and economic development play a major role in determining thermal comfort standards because people tend to do what they want if they can afford it (Humphreys, 1995, pp. 3-13; Leaman and Bordass, 1999, pp. 8; Oseland, 1993). Humphreys argued that "it is technically possible to have warm indoor temperatures in cold climates, and very cool temperatures in hot climates. It is costly and may deplete the earth's resources and pollute its atmosphere."[87,88,89] Local climate has a big influence on the preferred comfort temperature. This is the essence of the importance of this research because developing countries with limited energy resources and growing populations should invest more resources establishing comfort-standards for energy-efficiency.

Importance of the Research

Equatorial Climate is Unique

A major reason for this study was the fact that an equatorial highland climate has major points that are usually overlooked. Such items are translated into high-energy design strategies and costs to cover unnecessary mechanical systems. For perspective, the climate of Nairobi is compared with Gainesville, Florida (29.7ºN) and New York, New York (40ºN) in USA in several graphs that follow.

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[86] Standeven, M. A. and Nick V. Baker. 1995. Comfort conditions in PASCOOL surveys. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century*. Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 161-168.

[87] Humphreys, Reverend M. A. 1995. Thermal comfort temperatures and the habits of hobbits: Comfort temperatures and climate. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century*. Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 3-13.

[88] Humphreys, Reverend Michael A. 1981. The dependence of comfortable temperature upon indoor and outdoor climates. *Bio-engineering, Physiology and Comfort*. Amsterdam: Elsevier Science Limited.

[89] Milne, G. R. 1995. The energy implications of a climate-based indoor air temperature standard. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century*. Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 182-189.

First, Figure 3 gives a comparison between the numbers of degree-days at these three latitudes. It shows an equatorial highland with moderate climate. Seasonal changes are neither very wide nor severe. Because diurnal variations are large, they are used as the means of determining critical climate-responsive design strategies. New York has severely cold winters while Gainesville has severely hot summers.

Second, Figure 4 shows the comparison with regard to daylight hours. Daylight changes with distance away from the equator. On average, Nairobi receives 12 hours of daylight. Higher latitudes have long days during the summer solstice and short days during the winter solstice. From January to December, the equator has 12 hours of daylight and 12 hours of night approximately. At higher latitudes, there are four distinct seasons; at the equator there is only one long season defined by the monsoon rains.

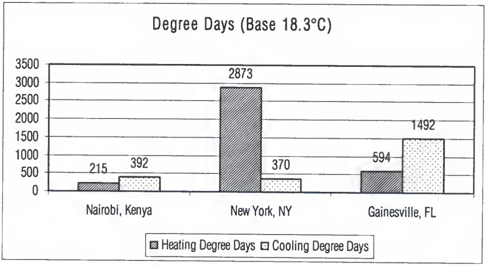

Figure 3: Annual degree-days for Nairobi, Gainesville and New York

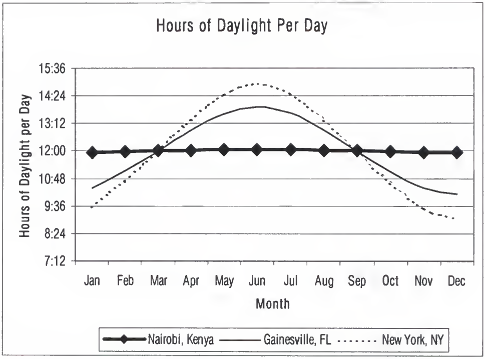

Figure 4: Hours of daylight annually

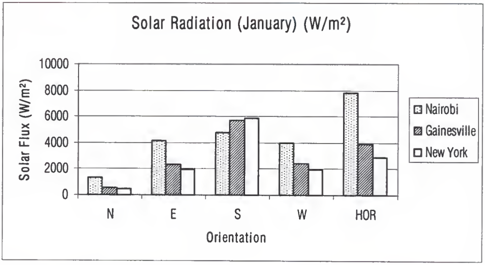

Figure 5: January radiation in Nairobi, Gainesville and New York

Solar radiation is strong, especially on a horizontal surface (Figure 5). Given the movement of the earth with respect to the sun, the highest radiation is received in

January/February and the least in July. Solar radiation on various orientations is shown in Figure 6.

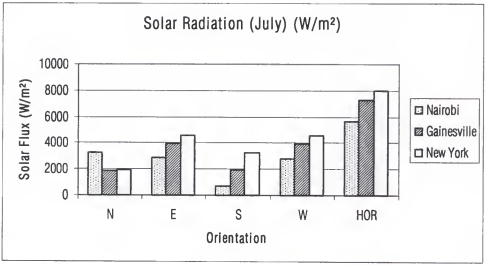

Figure 6: July radiation in Nairobi, Gainesville and New York

Temperature at high altitude near the equator is generally constant throughout the year. In fact, the equator experiences only one long season divided by long-rain and short-rain periods. Daily temperatures in January and July are given below.

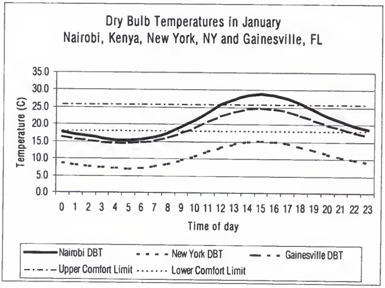

Figure 7: January Temperatures in Nairobi, Gainesville and New York

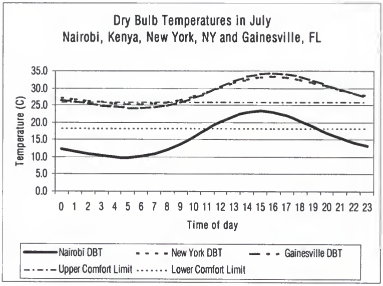

Figure 8: July Temperatures in Nairobi, Gainesville and New York

A thorough discussion of the equatorial high-altitude climate of Nairobi and its effect on thermal mass is given in Chapter 3.

Economic Growth for Developing Countries

The importance of this research stems from the fact that developing countries are finding it increasingly hard to cope up with rising costs of living on one hand and the issues of governance on the other. The United Nations said: "while the majority of the world's population grows richer, the poorest 20% - over 1 billion people – are so poor that they are effectively excluded from almost every benefit of modern society. This situation is not only unjust. It increasingly threatens, through waste of human resource, population movements and, in some regions, escalating crime rates, to undermine social stability and future economic growth."[90] The key to the development of a nation is sound energy policies. While developed countries have better technologies and higher economic capacities to deal with high-energy costs, least-developed nations have fewer options. This calls for the need to seek, through research, the means for better energy accounting. Buildings use significant amounts of energy and this impacts the economy of a nation. Economists Goudzwaard and de Lange in *Beyond Poverty and Affluence: Toward an Economy of Care*,[91] discussed some practical strategies that all nations have to take fight poverty. The rich and the poor have to co-operate to make everybody prosperous.

Building-Related Illness and Indoor Air Quality

Building-related illnesses and indoor air quality are a growing concern. The World Health Organization and Worldwatch[92] have said that 30% of the world's modern buildings are "sick". The UN General Assembly received reports on how man-made greenhouse gas emissions have reached highest concentrations in 200,000 years.[93] Some members urged other nations to adopt binding targets for green house reduction.[94] Indoor and outdoor climates need protection from dangerous emissions resulting greater use of energy. ASHRAE (1997, pp. 18.1) acknowledged the environmental consequences of a refrigerant that leaks from a system because of the adverse effect on the depletion of the ozone layer, which has worsened through the use of CFC refrigerants in HVAC systems.

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[90] UN: United Nations: Commission on Sustainable Development. 1997a. Global Change and Sustainable Development: Critical Trends. http://www.un.org/dpcsd/dsd/trends.htm.

[91] Goudzwaard, Bob and Harry de Lange. 1995. *Beyond Poverty and Affluence: Toward an Economy of Care*. WCC Publications 1211 Geneva 20, Switzerland and William B. Eardmans Publishing Company, Grand Rapids, Michigan.

[92] Worldwatch Paper 124, March 1995. Jane A. Peterson (ed). *Building Revolution: How Ecology and Health Concerns are Transforming Construction* by David Malin and Roodman and Nicholas Lenssen. Worldwatch Institute, 1776 Massachusetts Ave., NW Washington DC 20036. Also found at http://www.worldwatch.org/pubs/paper/124.html.

[93] UN: United Nations. 1997b. General Assembly is told man-made greenhouse emissions have reached highest concentrations in 200,000 years. *Press Release GA/9271 ENV/DEV/437*. http://www.un.org.

An effort made to acknowledge this problem was the formulation and signing in 1989 of the Montreal Protocol that controlled the production of ozone-depleting substances.[95] Later, the Copenhagen Amendment, entered into force on June 14, 1994, called for a complete cessation of the production of CFC's by January 1, 1996.

Air conditioning has a direct effect on indoor air quality. Refrigerants are the working fluids in refrigeration, air conditioning, and heat pumping systems. They absorb heat from one area, such as an air-conditioned space, and reject it into another, such as outdoors, usually through evaporation and condensation respectively.[96] They affect indoor air quality. Closely related to this, the US Environmental Protection Agency (EPA[97]) called indoor air quality (IAQ) one of the top environmental health risks. EPA discussed many topics related to sick building syndrome,[98] and ventilation and indoor air facts.[99] The World Health Organization rule of thumb is that "a pollutant released indoors is 1000 times more likely to reach people's lungs than a pollutant released indoors."[100]

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[94] UN: United Nations. 1997c. Binding targets for greenhouse gas reduction must be adopted in Kyoto, Japan tells economic and financial committee. *Press Release GA/EF/2788*. http://www.un.org.

[95] UN: United Nations. 1994. *1994 Report of the refrigeration, air conditioning, and heat pumps technical options committee*. United Nations Environmental Programme, Nairobi, Kenya.

[96] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition)*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. Chapter 18: Refrigerants.

[97] EPA: Environmental Protection Agency http://www.epa.gov

[98] EPA (Environmental Protection Agency). 1991. Indoor Air Facts No. 4 (Revised). *Sick building syndrome.* (http://www.epa.gov/iaq/sbs.html).

[99] EPA: Environmental Protection Agency. Fact sheet: Ventilation and air quality in offices. EPA (Environmental Protection Agency). 1990. Fact Sheet. 402-F-94-003. *Ventilation and Air Quality in Offices*. http://www.epa.gov/iaq/pubs/ventilat.html.

[100] World Health Organization. 2000. *Air Pollution, Fact Sheet No. 187* Revised September 2000 at http://www.who.int/inf-fs/en/fact187.html.

Many building-related illnesses are constantly being reported with fatalities in some cases.[101] Researchers at Lawrence Berkeley National Laboratories[102] suggested that US companies can save as much as $58 billion annually by preventing building-related illnesses and an extra $200 billion IAQ improvements for better worker performance.

Definition of Thermal Mass

Socrates,[103] as a thinker, demanded that important words be defined prior to their use in discussion. Consequently, a few key definitions are given in Appendix 1. Thermal mass is a term given to dense building materials used for walls, floors and roofs. These materials such as stone, concrete and brick tend to have high density and heat capacity.[104] Therefore, thermal mass, by definition from ASHRAE, "should store significant amounts of thermal energy. It can also delay heat transfer through a building component. This delay leads to a slower response time that tends to moderate indoor temperature fluctuations under outdoor temperature swings. Thermal mass can be used to move off-peak energy demand" (ASHRAE, 1997, pp. 39.12). Besides creating a useful delay in heat transfer, thermal mass also has a moderating effect since some absorbed heat energy is not re-radiated. Figure 9 explains the passive energy flow through building mass.

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[101] Conlin, Michelle. 2000. Is your office killing you? The dangers of sick buildings in *Business Week* June 5, 2000 pp. 114 – 128. New York: McGraw-Hill Companies. www.businessweek.com.

[102] Ibid. pp. 118.

[103] Cited by Gale, George. 1992. *Theory of Science*. New York: John Wiley & Sons, in Chapter 3: Theories and Paradigms, pp. 55.

[104] Lechner, N. 1991. *Heating, Cooling, Lighting: Design Methods for Architects*. New York: John Wiley & Sons, pp. 110.

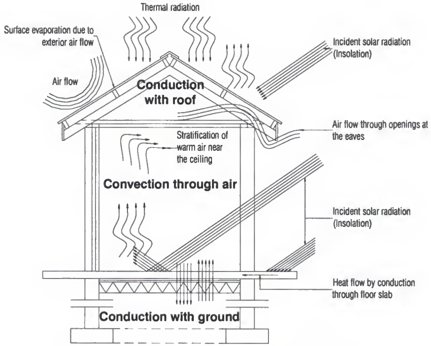
Thermal radiation
Surface evaporation due to exterior air flow
Air flow
Conduction with roof
Incident solar radiation (Insolation)
Air flow through openings at the eaves
Stratification of warm air near the ceiling
Convection through air
Incident solar radiation (Insolation)
Heat flow by conduction through floor slab
Conduction with ground

Figure 9: Passive energy flows

Major Theoretical Issues

Historical Issues of Thermal Environment Studies

Kinzey and Sharp[105] discussed some applications of environmental technologies in architecture. They discussed some of the techniques that were used to cool or heat buildings from early development of mechanical systems and the technological factors involved. These techniques were based more on conceptual experience rather than scientific understanding of their physical processes (Santamouris and Asimakopolous, 1996, pp. 2). Some of the applications were simple: appropriate technology, local building materials, shade and natural ventilation for comfort cooling or direct solar gains for heating. In climates where people wore light clothing, buildings were generally built with light mass. Conversely, where people wore heavy clothing, the buildings tended to be high mass.

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[105] Kinzey, Bertram and Howard M. Sharp. 1963. *Environmental Technologies in Architecture.* Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

This trend can be observed in many climates. In *Thermal Delight in Architecture*, Lisa Heschong discusses ways in which people adapted to different climates. She refers specifically to thermal mass and says:

> Vernacular buildings all over the world display remarkably sophisticated thermal adaptation. Primitive builders consistently used forms and materials that effectively moderated prevailing climatic conditions. In the desert the characteristic problem is extremely high daytimes coupled with uncomfortably low temperatures at night. The ideal building material would have a high heat capacity in order to absorb solar radiation during the day and slowly reradiate it at night.[106]

The process by which architectural design is developed in response to climate was given the name "Bioclimatic" by Olgyay in 1963[107]. He was the first to develop an integration of design and climate into a comfort chart by the same name, which is still used today (Figure 10). Four interacting environmental forces define it: radiant and ambient temperatures, relative humidity, and air movement with assumptions regarding activity and clothing levels.

The "building bioclimatic chart" by Givoni followed in 1969 with several other thermal indices and was later revised in 1976.[108] It was a precise method showing the properties of moist air with the applicable design strategies. In summary, the chart showed that high thermal mass is very useful in hot dry conditions where evaporative cooling is most effective. After many experimental studies, this chart was revised in 1998 showing the different strategies and boundaries of the passive solar approaches for summer and winter conditions. Figure 11 shows this information with comfort zones as proposed by ASHRAE and Givoni.

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[106] Heschong, Lisa. 1979. *Thermal Delight in Architecture*. Cambridge, Massachusetts: The MIT Press pp. 8.

[107] Olgyay, Victor. 1963. *Design With Climate. A Bio-Climatic Approach To Architectural Regionalism.* New Jersey: Princeton University Press. Now published by Van Nostrand Reinhold, New York, pp. 22.

[108] Givoni, Baruch. 1976. *Man, Climate and Architecture*. Applied Science Publishers, London pp. 314-319.

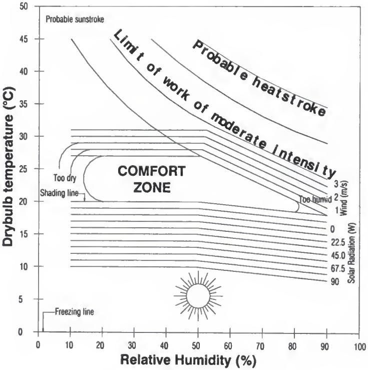

Figure 10: Bioclimatic Chart in metric units
Adapted from Olgyay, 1963, pp. 22

Thermal mass has a major role in passive cooling and passive heating where it can retain thermal energy from the sun and re-radiate it as needed (Figure 11). Thermal mass provides time lag and moderating effects through the structure. Givoni (1998b, pp. 189) showed that thermal mass is more effective in lowering indoor temperatures by about 3-4°C below outdoor temperatures when combined with nighttime ventilation.

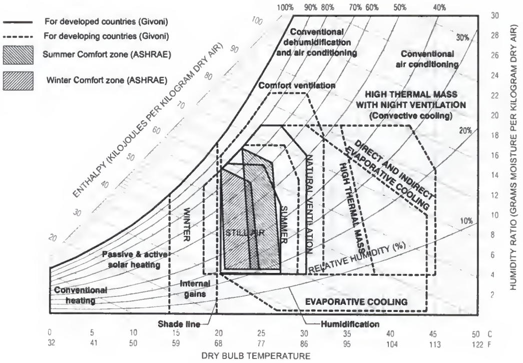

Figure 11: Psychrometric chart showing comfort zones and design strategies
Based on information from ASHRAE[109] and Givoni[110]

Before the energy crisis of 1973, Richard Stein[111] wrote an article in *Architectural Forum* magazine and argued that there was an anomaly with the fact that buildings were being designed irrespective of their regional context. At the time, most American architects were confident that no matter the orientation of unshaded glass they were capable of controlling the thermal environment. Stein[112] later wrote *Architecture and Energy: Conserving Energy Through Rational Design.* Availability of cheap energy had often allowed building designers to limit thermal control mechanisms mainly to mechanical systems. Rather than develop some proven passive solar methods, many of these methods were abandoned. As it appears, many people took immediate steps by looking for answers upwards - to the sun. Resurgence of solar design has had an up-and-down history this past century. Society may be served well by rediscovering the connection of climate, environment and architecture. It has been said that environmental forces shape architecture.

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[109] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition).* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. pp. 8.12.

[110] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design.* New York: Van Nostrand Reinhold pp. 45.

[111] Stein, Richard G. 1973. Architecture and Energy in Architecture Forum (July/August 1973) pp. 38-58.

[112] Stein, Richard G. 1977. *Architecture and Energy: Conserving Energy Through Rational Design.* Garden City, NY: Anchor Press/Doubleday.

Environmental Forces That Shape Architecture

In their book, *American Building: The Environmental forces that shape it,* James Marston Fitch (with William Bobenhausen)[113] refer to the comfort zone as the "thermal habitat of man as defined by four interacting environmental forces – radiant and ambient temperatures, relative humidity and air movement". They discuss the forces that a human body experiences to be in thermal equilibrium. Generally:

> The body has four channels for disposing of its excess heat: under normal room conditions, about 60% by radiation to surfaces colder than itself, about 15% by combination of convection from skin and mucous membrane, and conduction, and about 25% by evaporation from skin and mucous membrane.[114]

Givoni (1976) worked on this very subject in great detail. There are thermal mass elements that contribute to human comfort; the flow of heat by conduction is standing barefoot on cool floors or sitting on a cool surface. It introduces another concept that Fitch and Bobenhausen refer to as "Architecture – the Third environment". Thus:

> Human beings were compelled to invent architecture in order, ultimately, to become human. By means of it we surrounded ourselves with a new

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[113] Fitch, James Marston with William Bobenhausen. 1999. *American Building: The Environmental forces that shape it.* New York: Oxford University Press pp. 40.

[114] Ibid pp. 39.

> environment tailored to his specifications, interposed between the world and ourselves.[115]

McCleary talked of nature, super nature and super-super nature. These ideas are important in the way architecture is executed presently and also in future. Architecture is a process. The art and science of design must adapt new forms of expression as technology advances while at the same time not loose its real intention – human comfort. Finally they suggest that:

> The task of architecture, then, is not merely to abolish gross thermal extremes (freezing to death, dying of heat prostration) but to provide the optimal thermal environments for the whole spectrum of modern life. The technology of heating and cooling aims not merely at introducing the proper amount of heat into, or extracting the proper heat out of, the building: but to do it in such a manner as to achieve a thermal steady state across time - and a thermal equilibrium across space. Neither of these criteria is easy to achieve, as radiant and ambient heat are very unstable forms of energy.[116]

The idea of thermal equilibrium has been challenged by the concept of thermal boredom (Heschong,1979; Kwok, 2000). Anecdotal evidence seems to suggest that thermal mass can offer moderation for thermal environments conducive for long-term human comfort. Fanger (1967,[117] 1970,[118] 1972[119]) and Fitch with Bobenhausen refer to the physical environmental factors that affect thermal comfort as are summarized in the figure below. The acoustic factors discussed by Siebein (1993) in *Tutorial on Architectural Acoustics* are also included in the diagram summary.

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[115] Ibid. pp. 15.

[116] Ibid. pp. 45.

[117] Fanger, P. O. 1967. Calculation of thermal comfort: Introduction of a basic comfort equation. *ASHRAE Transactions* 73 (2) pp. III 4.1-4.20.

[118] Fanger, P. O. 1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering*. New York: McGraw-Hill Book Company pp. 15.

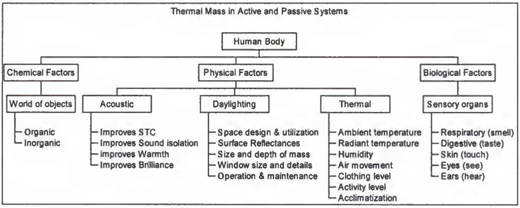

Figure 12: Physical Environmental factors that affect the human body
Source: Based on Fanger, [120] Fitch,[121] IESNA[122] and Siebein[123]

The masters of architecture celebrated the aspects in design shown in the above figure. The works of Aalto, Kahn, Mies, Wright, among others, have controlled the sensory environmental qualities such as heat, light, sound, etc. to accentuate their design concepts. These visible physical factors can be measured. There are also other factors that are invisible. Le Corbusier[124] made this argument when he wrote about "Architecture, pure creation of the mind":

> Architecture only exists when there is a poetic emotion. Architecture is a plastic thing. I mean by "plastic" what is seen and measured by the eyes. Obviously, if the roof were to fall in, if the central heating did not work, if the walls cracked, the joys of architecture would be greatly diminished;

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[119] Fanger, P. O. 1972. *Thermal Comfort.* McGraw-Hill Book Company, New York.

[120] Fanger, P. O. 1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering.* New York: McGraw-Hill Book Company pp. 15.

[121] Fitch, James Marston with William Bobenhausen. 1999. *American Building: The Environmental forces that shape it.* New York: Oxford University Press, pp. 8-11.

[122] IESNA: Illuminating Engineering Society of North America. 2000. *Lighting Handbook* 9th edition. New York: Illuminating Engineering Society of North America. Ch 26: Energy management pp. 26-6.

[123] Siebein, Gary W. 1993. *Tutorial on Architectural Acoustics.* University of Florida, Gainesville, FL.

[124] Le Corbusier. 1931. *Towards a New Architecture* translated by Fredrick Etchells, New York: Dover Publications, Inc. pp. 215. This Dover edition, first published in 1986, is an unabridged and unaltered republication of the work originally published by John Rodker, London, in 1931, as translated from the thirteenth French edition and given in English introduction by Fredrick Etchells.

> the same things might be said of a gentleman who listened to a symphony sitting on a pin-cushion or in bad draught.[125]

Le Corbusier implies that the visual impact and thermal sensations of architecture should be concealed so that the aesthetics of architecture can be fully realized. This could mean that "what is seen" in mechanical systems should be hidden in thermal elements, like thermal mass, while still providing the crucially needed thermal comfort. It leads to the challenges designers face in providing thermal comfort. Many different climates around the world require strategies that directly impact the availability, cost and effects of energy use. Clothes worn on the outside manipulate the thermal environment of an individual depending on the insulation film, color and surface film. In a similar way, a thermally massive building manipulates the larger environment for social interactions. Technology is transforming buildings in ways hitherto unknown. Indoor climates are now mechanically controlled regardless of outdoor conditions. The desired level is achievable through codes and standards currently in practice. In 1969, Charles Jencks predicted:

> With modern techniques, indoor and outdoor are merging, as are the qualities of day and night, summer and winter and north and south. Soon large portions of the population will inhabit a city-country which is air-conditioned, lit for the twenty-four hour cycle, fully serviced and alive with activity for a continual period. Already parts of every megalopolis have these pockets of totally artificially environment where the natural cycles have become fully obscured: any large airport terminal for instance.[126]

Jencks' prediction is with us today. Buildings are being erected around the world that do not respect their local climatic considerations. Konya alluded to the same fact in his book *Design Primer for Hot Climates.*[127] He discussed how humanity has forgotten to design with nature by ignoring the local climate while being preoccupied with forms currently fashionable: "The modern building – office or dwelling – looks much the same the world over because, among other things, it has been designed largely to keep natural phenomena outside, to separate conditions inside from the outdoors as much as possible, relying on mechanical devices and systems for air conditioning". A new energy paradigm is needed that places a building in its context at the same time have provisions for acceptable human comfort response. Buildings have their own internal environments but they also are part of the larger environment.

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[125] Cited also by Odoerfer, Joseph B in *The Poetics of Thermal Technology* as Chapter 21 in Construction and Building Construction.

[126] Jencks, C. 1971. *Architecture 2000: Predictions and Methods*. New York: Praegaer Publications, pp. 117.

Passive Solar Energy as a Solution to Energy Problems

Yannas[128] discussed solar energy and housing design in Britain and said that it is worth considering low energy design for the following reasons:

1. Energy savings
2. Positive effect on the environment
3. Reduced dependency on conventional energy supply
4. Improvement of thermal and visual comfort
5. Improves amenity and added market value to the building
6. Cuts costs and is cost-effective
7. Provides potential for innovative design

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[127] Konya, Allan. 1980. *Design primer for hot climates*. London: The Architectural Press pp. 7.

[128] Yannas, Simos. 1994. *Solar Energy and Housing Design*. London, UK: Architectural Association pp. 22.

Yannas went on to explain why low energy design is not more widely adopted despite these tremendous benefits.[129] They are:

1. Lack of design information: There is insufficient published information on design principles and performance data.
2. Credibility and applicability: There is a mistaken belief that low-energy design involves unusual, unconventional or unreliable devices.
3. Marketability: The potential market value is not yet widely recognized by developers, even though surveys suggest a growing environmental consciousness among buyers.
4. Lack of incentive: Low fuel prices and lack of positive incentives for saving energy have acted as constraints.
5. Costs: There is a mistaken belief that the design process will take longer and require more effort and that the building costs will be high.
6. Design quality: Few built examples have been of outstanding architectural quality to act as exemplars.

At the time of the oil crisis in 1973, many building regulations around the world did not require that buildings incorporate thermal insulation. The ability to control the thermal environment inside buildings was threatened because low cost energy for daily social and economic life had been taken for granted for so long. This changed immediately. By the 1990's, insulation alone was perceived to be the only energy-efficient strategy needed. One of the lessons now being learnt is that climate-sensitive design improves thermal comfort and environmental quality.

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[129] Ibid pp. 23.

Immediate responses to the energy crisis were developments like *ASHRAE Standard 55*[130], *ASHRAE Standard 62*[131], *ASHRAE Standard 90.1*[132] and *ASHRAE Standard 90.2*[133]. These standards are prescriptive in nature (insulation, ventilation rates, glazing types, lighting systems and efficiency of systems), and have their roots from the 1970's when the energy crisis was most severely felt. The energy crisis, in part, led to the prevalence of sick-building syndrome because buildings were highly insulated and kept airtight for energy-conservation. Ventilation rates once were as low as 5 CFM (cubic feet per minute) per person.[134] In a recent issue of *ASHRAE Journal* (August 1999), Stanke discussed a perspective of ventilation through the years, from 1973 to date, by showing how and why ASHRAE recommendations rates have evolved with time.[135]

There was a flurry of activity in the 1980's regarding solar energy applications but this has slowed down again. Some policy-makers in many governments around the world argue that the technology needed to make solar energy viable is expensive and needs a lot of capital. However, the work by NASA in space is a testimony that determined research in solar energy can yield positive results. Today's hand-held calculator can use readily available solar energy; it is a product resulting from the need to make high-performance computations using low levels of renewable energy.

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[130] ASHRAE. 1992. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard 55-1992.* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[131] ASHRAE. 1989. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62-1989. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[132] ASHRAE. 1989. Energy-efficient design of new buildings except low-rise residential buildings. ASHRAE/IESNA *Standard* 90.1-1989. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[133] ASHRAE. 1993. Energy-efficient design of new low-rise residential buildings. ASHRAE/IESNA *Standard* 90.2-1993. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[134] ASHRAE. 1974. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62-1974. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[135] Stanke, Dennis. 1999. Ventilation through the years: A perspective. *ASHRAE Journal*, Vol. 41, No. 8, pp. 40-43. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

Energy-conscious architecture has moved from just solar collectors on roofs to the building itself. While passive solar architecture does not have the fanfare of the 1980's, it is still feasible in many places around the world. Dr. J. Douglas Balcomb at Los Alamos National Laboratory and National Renewable Laboratories led research in *Passive Solar Buildings*. The main theme from these studies was that architects must fully understand local climate if energy-efficiency was to be achieved.

Although not directly related to thermal mass, emerging technologies such as building-integrated photovoltaic designs are also growing steadily in communications, rural site electrification, remote power, vaccine refrigeration, remote monitoring stations, water pumping and battery charging.[136],[137],[138],[139],[140],[141],[142],[143]

The use of thermal mass can be optimized using number of equations developed from this study. Some studies[144] show that passive systems (cooling, heating and lighting) have a bigger influence on architectural form than active systems. Not all energy issues can profoundly affect architectural form, but architectural form can profoundly affect energy use. These matters have largely been ignored in many Schools of Architecture.

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[136] 1999 ASHRAE Applications Handbook, Chapter 32, pp. 32.26.

[137] 2000 ASHRAE Systems and Equipment Handbook, Chapter 33 pp. 33.20.

[138] Goswami, *et al.* 2000.

[139] *Solar Today*. 1998. Vol. 12, No. 6. PV in Paradise by James Bing, pp. 26-29. Boulder, CO: The American Solar Energy Society.

[140] *Solar Today*. 1999. Vol. 13, No. 1. Solar energy in Europe by Pamela Murphy Kunz, pp. 28-31. Boulder, CO: The American Solar Energy Society.

[141] *Solar Today*. 1999. Vol. 13, No. 2. The ABC's of solar living by David and Brenda Hrivnak. pp. 34-37. Boulder, CO: The American Solar Energy Society.

[142] *Solar Today*. 1999. Vol. 13, No. 3. PV powers rural communities by Andre Verani, Chad Nielsen and Philip Covell. pp. 30-33. Boulder, CO: The American Solar Energy Society.

[143] *Solar Today*. 1999. Vol. 13, No. 6. Electrifying the un-electrified by John Perlin Balcomb, pp. 26-29. Boulder, CO: The American Solar Energy Society.

Energy Performance of a Building

In *Low energy strategies for non-domestic buildings,* Baker[145] proposed that the energy performance of buildings is due to three factors, namely as:

1. That which is inherent in the *building* design
2. That which relates to services *systems* design and efficiency
3. That which is due to the effect of *occupant* behavior.

Baker suggested that the final performance is a product of *building, systems* and *occupant* interactive factors. Figure 13 summarizes relative contribution of these factors.

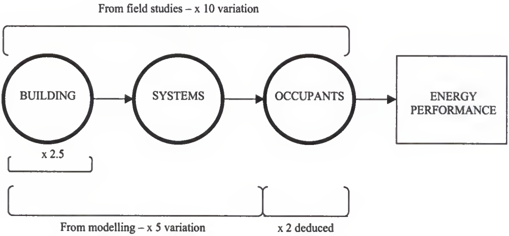
From field studies – x 10 variation
BUILDING
SYSTEMS
OCCUPANTS
ENERGY PERFORMANCE
x 2.5
From modelling – x 5 variation
x 2 deduced

Figure 13: Relative contribution of building, systems and occupant factors on energy use
Source: Baker, 1992, pp. 247

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[144] Brown G. Z. 1985. *Sun, Wind and Light: Architectural Design Strategies*. New York: John Wiley & Sons pp. vii.

[145] Baker, Nick. 1992. Low energy strategies for non-domestic buildings. Roaf, Susan and Mary Hancock (ed). 1992. *Energy-efficient building*. New York: John Wiley & Sons, pp. 246-259.

Baker argued that a deep plan would result in certain building performance demanding heating, cooling and lighting for an idealized occupant. The efficiency of building *systems* plays a key role in the overall performance. *Occupants* (and management) who operate building systems in a non-optimal fashion can decrease performance.

Baker said that if *systems* and *occupant* factors are fixed, the range of energy use due to *building* alone is unlikely to be greater than about 2.5 fold. When *systems* are varied also, then the energy consumption range increases five fold, implying that *occupant* factors account for a twofold variation. Efficient *systems* can replace older *systems* even after a building is complete, and *occupants* can be educated to manage their buildings better. *Building* factors are hard to adjust or alter after construction. Therefore, *building* elements (particularly the use and location of thermal mass!) have profound implications on architecture and energy performance. More emphasis is needed on the systems/mass interaction, hence this study.

Conclusions

Architecture is a process[146] – from inception, through design development to completion. Basic design decisions have energy consequences. Energy is used to run and maintain buildings. Energy consumption in buildings is related to the local climate, building systems, occupancy patterns and the thermal properties of the building materials. Energy use is important concern because it affects (1) the choice of building materials and methods (2) architectural form and layout planning (3) response to site and natural features. Some building materials waste energy while others, such as those where thermal mass is applicable, conserve cooling and heating energy. Not all energy issues can profoundly affect architectural form, but architectural form can profoundly affect energy use. Psychological expectations have a bearing on the use energy in buildings.

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[146] CEC: Commission of European Communities. 1990. *Passive solar energy as a fuel – 1990-2010.* Executive Summary, Commission of European Communities, DGXII, pp. 29.

CHAPTER 2
EXPERIMENTAL STUDY ON THERMAL MASS

Introduction

This chapter discusses a model study carried out to test the effect of thermal mass on comfort conditions. Specifically, the experiment tested the effectiveness of high thermal mass in moderating indoor temperatures, and thus improving comfort conditions. It was conducted in Nairobi, Kenya, which is an equatorial high altitude region. Precisely, Nairobi is at 1.3° S latitude at an altitude of 1798m (5900 feet) above sea level. This chapter is a presentation of measurements taken in the four test houses and discusses the work that has been done on this subject in other studies, principally by Baruch Givoni and J. Douglas Balcomb. Lord Kelvin[1] (1824-1907) said:

> When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.

Experiments on Thermal Mass: An Overview

The work by Givoni (1998a)[2] is among the latest and probably the best on this subject. He monitored buildings with different mass levels under different ventilation and shading conditions in the summer of 1993 in Pala in Southern California in the USA. The lowering of the daytime indoor temperatures was evaluated. Givoni found that night ventilation was effective in lowering indoor temperature for a high mass building below the outdoor maximum. He reported that on an extremely hot day with outdoor maximum of 38°C (100°F), the indoor maximum temperature of the high mass building was only 24.5°C (76°F), which is well within the comfort zone for the humidity level of California.

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[1] Cited by IESNA: Illuminating Engineering Society of North America. 2000. *Lighting Handbook* 9th edition. New York: Illuminating Engineering Society of North America, pp. 2-1.

[2] Givoni, Baruch. 1998a. Effectiveness Of Mass And Night Ventilation In Lowering Indoor Daytime Temperatures. Part I: 1993 experimental periods. *Energy and Buildings* 28 (1998) 25-32. Amsterdam: Elsevier Science Limited.

While in Israel at Ben Gurion University of the Negev,[3] Givoni conducted more research on the performance of two full-size rooms (3 x 4m) (10' x 13' approximately) with high mass. He used walls of 200mm (8") concrete, insulated towards the external side. The exterior color was off-white. He found that when buildings have white envelope color, night ventilation lowered the maximum temperature by about 2°C as compared to a dark building. These results were reported more precisely in 1998.[4] Another study[5] was made using an insulated passive wall design to minimize building temperature swings. Most recently, Givoni and Noguchi have studied and established some issues in outdoor comfort research.[6] Insulation decouples the mass from exterior temperatures. This affects the behavior and location of thermal mass.

For many years, Balcomb has led a team of researchers at the Los Alamos National Laboratories and the National Renewable Energy Laboratories in passive and low energy architecture. They developed design software called *Energy-10* that can investigate design strategies like passive solar heating and daylighting. It assists pre-design decisions such as when thermal mass is beneficial to the design. The following recommendations are made regarding the benefits of the use of thermal mass:

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[3] Givoni, Baruch. 1976. *Man, Climate and Architecture*. Applied Science Publishers, London, pp. 120-144.

[4] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. New York: Van Nostrand Reinhold, pp. 187-188.

[5] Duffin, R. J. 1984. A passive wall design to minimize building temperature swings. *Solar Energy* 33 (3/4) (1984) 319-326. New York: Pergamon Press.

> Dense building materials with the right mix of thermal conductivity and heat capacity, such as brick, concrete and concrete block, store and release considerable amounts of energy when they rise and fall in temperature. … Thermal mass is particularly effective in regions where the outdoor air temperature fluctuates daily above and below the building balance point (the exterior temperature at which a building is in equilibrium with heat gains equaling heat losses).[7]

Studies[8,9,10,11] show that the color of thermal mass is a significant factor in heat transfer. Light-colored surfaces reflect most of the solar radiation while dark surfaces absorb 70-90% of it (Balcomb 1996, pp. 106). The quantitative effect of the color of the envelope on the indoor air temperature, and on the energy demand of a building, depends on the thermal properties of the walls and roofs, climate, and ventilation conditions (Givoni, 1998b, pp. 78). Thermal mass surfaces should be large enough to store adequate heat and cold as required. In *Sun, Wind and Light*, Brown reported: "in order to be effective thermal masses for storing heat or cold, buildings must have exposed surfaces inside the space. Insulation, if needed, must be on the exterior side of the mass."[12]

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[6] Givoni, Baruch and Mikiko Noguchi. 2000. Issues in outdoor comfort research in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 562-564. James & James (Science Publishers) Ltd.

[7] Balcomb, J. Douglas. 1996. *Designing low-energy buildings: Passive solar strategies and Energy-10 Software*. Passive Solar Industries Council, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and US Department of Energy (DOE) pp. 105-110.

[8] Ibid. pp. 106.

[9] Givoni, Baruch. 1976. *Man, Climate and Architecture*. London: Applied Science Publishers, pp. 217.

[10] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. New York: Van Nostrand Reinhold, pp. 74.

[11] Santamouris, M. and D. Asimakopolous (ed). 1996. *Passive Cooling of Buildings*. London: James & James (Science Publishers) Ltd. pp. 192.

Thermal mass location, distribution, insulation and the role of ventilation are important matters that must be addressed if full thermal mass benefits are to be realized.

Modeling Techniques Involving Thermal Mass

Experiments (using physical models) and field studies have been the two major research methods of quantitatively and qualitatively studying various phenomena in buildings. Proper criteria need to be established to determine the best method to answer a research question. Experiments involving physical models and climate-chambers provide data that show what happens in controlled environments; field studies, on the other hand, provide data that show what happens in uncontrolled environments. Both methods have a role in adding knowledge, although there are potential conflicts that could arise out of conclusions drawn from both methods.

Recently, with the advent of personal computers, simulation programs have been developed using improved energy theory based on evidence from experiments and field results. They are important as a means to test different alternatives that would otherwise be difficult or expensive to study.

Victor Olgyay methodically documented the theoretical analysis of thermal effects of thermal mass in 1963[13]. Over the years, Givoni also made tremendous contribution to the body of knowledge on this subject by using physical models in Israel and in California. His book *Man, Climate and Architecture,* published originally in 1969 and revised in 1976, was a major research compilation of theoretical knowledge backed

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[12] Brown G. Z. 1985. *Sun, Wind and Light: Architectural Design Strategies*. New York: John Wiley & Sons pp. 124.

by enormous experimental evidence. The Florida Solar Energy Center (FSEC) in Cape Canaveral, Florida has engaged in numerous studies using full-scale models. Their publication in 1988 of *Energy-efficient Florida Home Building,*[14] among many others, is the result of such studies. Other studies have reported major success using physical models and climate-chamber experiments (Wilcox *et al.*;[15] De dear *et al.*;[16,17] and Wu[18]). J. Douglas Balcomb at Los Alamos National Laboratory and National Renewable Laboratories has led research in *Designing Low-Energy Buildings*[19] and measurement of passive solar performance. Balcomb contributed very important knowledge in several other key publications.[20,21] Recent studies by Givoni have examined the role of thermal mass on indoor temperatures.[22,23]

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[13] Olgyay, Victor. 1963. *Design With Climate. A Bio-Climatic Approach To Architectural Regionalism.* New Jersey: Princeton University Press. Now published by Van Nostrand Reinhold, New York. Chapter 10: Thermal Effects of Materials pp. 113-124.

[14] Florida Solar Energy Center (FSEC). 1992. Manual entitled: *Energy-efficient Florida Home Building* by Veira, Robin K., Kenneth G. Sheinkopf and Jeffrey K. Sonne at Florida Solar Energy Center (FSEC) Cape Canaveral, FL.

[15] Wilcox, B. et al. 1985. The effects of thermal mass exterior walls on heating and cooling loads in commercial buildings. *Proceedings of ASHRAE Building Envelopes Conference.* Atlanta GA: ASHRAE

[16] De Dear, R., K. Leow, and A. Ameen. 1991. Thermal comfort in the humid tropics – Part I: Climate Chamber experiments on thermal acceptability in Singapore *ASHRAE Transactions* 97 (1): 874-879. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[17] De Dear, R., K. Leow, and A. Ameen. 1991. Thermal comfort in the humid tropics – Part II: Climate Chamber experiments on thermal acceptability in Singapore *ASHRAE Transactions* 97 (1): 880-886. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[18] Wu, H. 1996. The Effect of Thermal Mass On Indoor Comfort with Evaporative Cooling Systems In Semi-Arid Climates. *Proceedings Of The National Passive Solar Conference 1996*; Vol 21 pp. 113-118.

[19] Balcomb, J. Douglas. 1996. *Designing low-energy buildings: Passive solar strategies and Energy-10 Software.* Developed in collaboration with Passive Solar Industries Council, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and US Department of Energy (DOE).

[20] Balcomb, J. Douglas. 1983. *Heat storage and distribution inside passive solar buildings.* Los Alamos National Laboratory, New Mexico Report LA-9694-MS, available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, USA.

[21] Balcomb, J. Douglas. 1984. *Passive Solar Design Handbook.* New York: Van Nostrand Reinhold.

[22] Givoni, Baruch. 1998a. Effectiveness Of Mass And Night Ventilation In Lowering Indoor Daytime Temperatures. Part I: 1993 experimental periods. *Energy and Buildings* 28 (1998) 25-32. Amsterdam: Elsevier Science Limited.

Most current theoretical knowledge has been developed from physical model experiments (controlled environments). As previously stated, the other major research method used in many thermal comfort studies has been the field study. This technique meets people in their normal environments, while performing their normal activities, and seeks their opinion *on-site*. In this case the researcher measures the environment without altering it. Humphreys[24] reported major results of this method in thermal comfort studies after a series of previous studies in 1975,[25] 1976[26] and 1978[27].

Santamouris and Asimakopolous[28] reported a series of case studies involving thermal mass; their studies have guided this literature search. Brown[29] monitored an office building and compared data with simulations using variable levels of thermal mass in similar buildings, and found that a ten-fold increase of thermal mass from 21 to 201 kg/m^2 of floor area, in closed and in ventilated buildings, can reduce the peak indoor temperature by approximately 1°C to 2°C. Ruud *et al.*[30] evaluated the effect of building thermal mass in offsetting cooling loads by conducting two experiments on the

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[23] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. New York: Van Nostrand Reinhold.

[24] Humphreys, Reverend Michael A. 1992. Thermal comfort in the context of energy conservation in *Energy-efficient building* edited by Susan Roaf and Mary Hancok. New York: John Wiley & Sons, Inc. pp. 3-13.

[25] Humphreys, Reverend Michael A. 1975. Field Studies of thermal comfort compared and applied. *Building Research Establishment*, Current Paper. CP 76/75, Garston, Watford, UK.

[26] Humphreys, Reverend Michael A. 1976. Field Studies of thermal comfort compared and applied. *Building Services Engineer*, 44, pp. 5-27.

[27] Humphreys, Reverend Michael A. 1978. Outdoor temperatures and comfort indoors. *Building Research and Practice*, 62, pp. 92-105.

[28] Santamouris, M. and D. Asimakopolous (ed). 1996. *Passive Cooling of Buildings*. London: James & James (Science Publishers) Ltd.

[29] Brown, M. 1990. Optimization of thermal mass in commercial building applications. *ASME Journal of Solar Energy Engineering*, 112 (1990) 273-279.

Independent Life Insurance building located in Jacksonville, Florida in USA. The results showed an 18% reduction in cooling energy supplied during the daytime based on nighttime ventilation on thermal mass.

Six test buildings were investigated by Burch *et al.*[31] to test the effect of wall mass on summer space cooling. The buildings were located at the US National Bureau of Standards in Gaithersburg, MD. They found that for indoor temperature set at 24° C, high mass buildings consumed less cooling energy than similar lightweight buildings with similar thermal resistance. They also found that thermal mass was more effective when positioned on the interior side of insulation. Burch *et al.*[32] also studied the effect of thermal mass on night-temperature setback savings and noticed a 40% reduction on sensible heating and cooling loads.

Sunaga and Ito[33] tested the role of thermal mass on various passive systems and noted the benefits of adobe buildings. Robertson presented specific recommendations on how best to use thermal mass in residential and small commercial buildings, for southwestern USA, in 1986.[34] These studies have provided important observations to other studies involving thermal mass.

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[30] Ruud, M. D., J. W. Mitchell and S. A. Klein. 1990. Use of building thermal mass to offset cooling loads, *ASHRAE Transactions*, 96 (2): 820-828. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[31] Burch, D., S. Malcolm and K. Davis. 1984. The effect of wall mass on the summer space cooling of six test buildings. *ASHRAE Transactions*, Vol. 90, No. 2B, pp. 5-21. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[32] Burch, D., W. Johns, T. Jacobsen, G. Walton, and C. Reeve. 1984. The effect of thermal mass on night temperature setback savings. *ASHRAE Transactions*, Vol. 90, No. 2A, pp. 184-206. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[33] Sunaga, N. and N. Ito. 1985. Experimental analysis of thermal mass effect on the indoor climate in passive solar heating system with test cells. *Proceedings of the International Symposium on Thermal Application of Solar Energy*, pp. 253-258, 7-10 April, Hakone, Japan.

[34] Robertson, D. 1986. The performance of adobe and other thermal mass materials in residential buildings. *Passive Solar Journal*, 3 (1986) 387-417.

Today, computational simulations also play a major role in testing and modeling techniques involving thermal mass. Ober and Wortman[35] ran a series of simulations of three building types (a warehouse, low-rise office building and a retail building) in four climatic zones in USA (Atlanta, Phoenix, New York and Minnesota). They reported that the wall thermal mass is more effective in office and retail buildings than in warehouses and buildings with high internal mass levels. These are some of the methods and results from previous studies. This study used an experimental method with four test houses.

Experimental Test Houses

Experimental Set-up

Four buildings were built and monitored on a site in Nairobi, Kenya. Each house measured 2.0m (6′ 7″) long by 2.0m (6′ 7″) wide and 2.0m (6′ 7″) high at wall plate level. Two houses were built with timber walls while the other two had natural stonework. Further more, the roof was made of galvanized corrugated iron (GCI) sheets and concrete interlocking tiles. The timber buildings were considered as low mass while the stone buildings as high mass. The heat loss coefficient (UA) was 120 W/°C (229 Btu/h °F) for the low mass building and 85 W/ °C (162 Btu/h °F) for the high mass buildings.

Givoni (1998a)[36] monitored three buildings with the same heat loss coefficient (96.5 W/ °C) (183 Btu/h °F) but with three different mass levels: a "low-mass" building (conventional stud-wall construction), a "medium-mass" building, and a "high-mass"

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[35] Ober, D. and D. Wortman. 1991. Effect o building type on wall thermal mass performance. *ASHRAE Transactions*, Vol. 33, No. 11, pp. 18-21. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

(insulated concrete walls). The heat loss coefficient in the high mass buildings by Givoni was approximately the same as the heat loss coefficient of two test buildings (stone-tile) used in this study. The houses are shown in Figure 14.

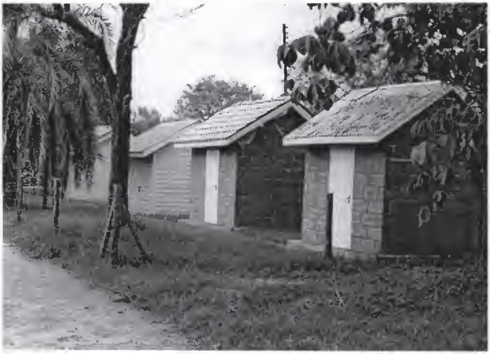

Figure 14: Four test houses in the experimental study

The vegetation on site was typical of the surrounding regional conditions. The compound was fenced off to keep out trespassers. The floor in all cases was a 100mm (4') thick concrete slab. The ceilings were made of a local papyrus-like material, called *Jambi* in Swahili,[37] with thermal resistance of 0.06 W/m^2 °C (0.011 Btu/h ft^2 °F). This material is fairly light in mass and it is light gray or light brown in color. The Table below shows calculated U-values across the roofs of the four houses.

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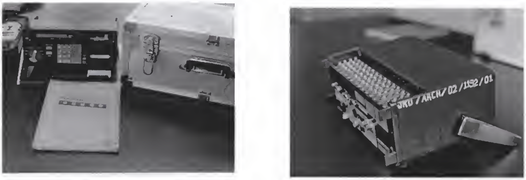
[36] Givoni, Baruch. 1998a. Effectiveness Of Mass And Night Ventilation In Lowering Indoor Daytime Temperatures. Part I: 1993 experimental periods. *Energy and Buildings* 28 (1998) 25-32. Amsterdam: Elsevier Science Limited.

[37] Swahili is the national language of Kenya, and is spoken widely in Eastern Africa. It is a Bantu dialect.

Table 1: Thermal Transmittance (U-values) in the four test houses

Ceiling configuration	*GCI sheet roof* *W/m^2 °C (Btu/h ft^2 °F)*	*Concrete tile roof* *W/m^2 °C (Btu/h ft^2 °F)*
Without ceiling	0.600 (0.106)	0.418 (0.074)
Slope ceiling	0.581 (0.102)	0.408 (0.072)
2/3 ceiling	0.360 (0.063)	0.246 (0.043)
Flat ceiling	0.360 (0.063)	0.246 (0.043)

The main instrument for data acquisition was the thermodac (Figure 15). It is a mobile measurement system that collects up to 60 parameters concurrently. The system meets ANSI/ASHRAE 55-92[38] and ISO 7726[39] standards' specifications for accuracy and response times. The instrument was in one house and cables were extended to all houses.



(a) Thermodac, Manual and Carrying Case (b) Top showing terminal points

Figure 15: Thermodac: data acquisition system for physical measurements

Plans and Sections of Experimental Test Houses

The layout for the houses is shown below. The test chamber in each case is shown as dimensioned and annotated. The two types of walling materials of stone and timber are shown. The other two types of roofing materials (galvanized corrugated iron sheets and interlocking concrete tiles) are shown also. The floor slab in all cases extended about 600mm (2') beyond the edge of the house.

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[38] ASHRAE. 1992. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard 55-1992.* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[39] ISO 7726. 1985. Thermal environments – Specifications relating to appliance and methods for measuring physical characteristics of the environmental. *ISO Standard 7726.* Geneva: International Standards Organization.

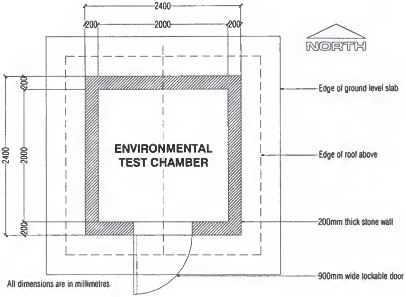
2400
200
2000
200
NORTH
ENVIRONMENTAL TEST CHAMBER
Edge of ground level slab
Edge of roof above
200mm thick stone wall
900mm wide lockable door
All dimensions are in millimetres

Figure 16: Floor plan of stone test house

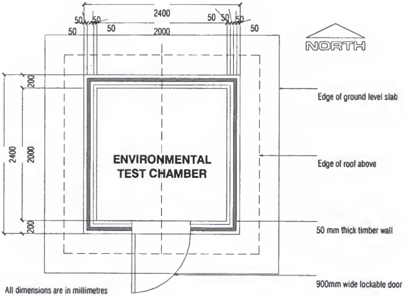
2400
2000
50
200
NORTH
ENVIRONMENTAL TEST CHAMBER
Edge of ground level slab
Edge of roof above
50 mm thick timber wall
900mm wide lockable door
All dimensions are in millimetres

Figure 17: Floor plan of timber test house

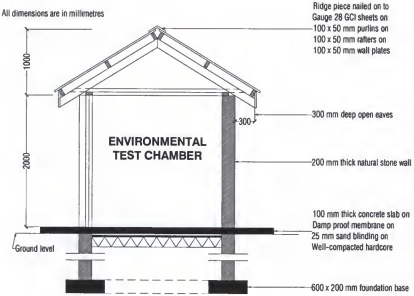

Figure 18: Section showing galvanized corrugated iron (GCI) roof

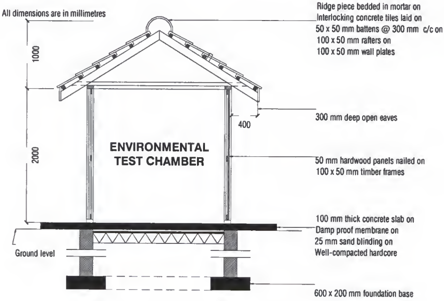
All dimensions are in millimetres
1000
2000
ENVIRONMENTAL
TEST CHAMBER
400
Ground level
Ridge piece bedded in mortar on
Interlocking concrete tiles laid on
50 x 50 mm battens @ 300 mm c/c on
100 x 50 mm rafters on
100 x 50 mm wall plates
300 mm deep open eaves
50 mm hardwood panels nailed on
100 x 50 mm timber frames
100 mm thick concrete slab on
Damp proof membrane on
25 mm sand blinding on
Well-compacted hardcore
600 x 200 mm foundation base

Figure 19: Section through test house showing tile roof

Experimental and Measurement Procedure

Each house was tested with four different ceiling configurations defined by the actual location within the roof space: no ceiling, slope ceiling, 2/3 ceiling and flat. The ceiling configurations are shown in Figure 25. Measurements were taken at 10-minute intervals for each house for a period lasting two weeks for each configuration. There were breaks of four days between sessions in which ceilings were re-configured. Therefore, the total time taken for this entire parametric arrangement was about twelve weeks. The monitoring instrument was kept in one house and six sensors per house were strategically positioned in all houses.

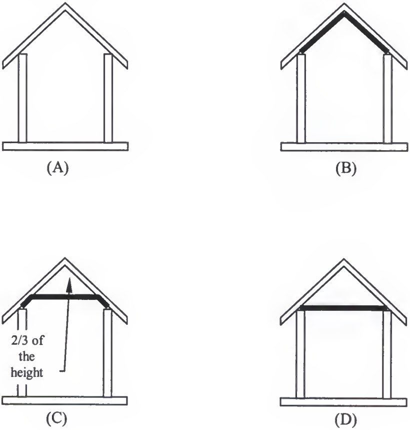

Figure 20: Diagrammatic sections that show the various ceiling configurations (A) No ceiling (B) Slope ceiling (C) Two-thirds ceiling (D) Flat ceiling

Each house had several measuring points suspended in the middle of the space at different heights. The instrument layout is shown below.

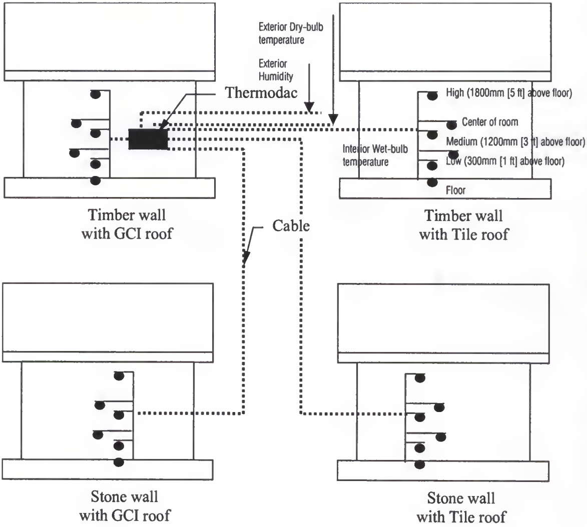
Exterior Dry-bulb temperature
Exterior Humidity
Thermodac
High (1800mm [5 ft] above floor)
Center of room
Medium (1200mm [3 ft] above floor)
Low (300mm [1 ft] above floor)
Interior Wet-bulb temperature
Floor
Timber wall with GCI roof
Cable
Timber wall with Tile roof
Stone wall with GCI roof
Stone wall with Tile roof

Figure 21: Instrument Layout connecting the four houses

Data Collection

Data were collected using the monitoring sensors of a thermodac (a device capable of measuring temperature using the principle of thermal couple). Sensors were attached to wall and floor surfaces, and also others were suspended in each house to take data defining the room conditions. These sensors[40] in each building measured:

(a) Mean radiant temperature (MRT) by globe thermometer (center of the room)

(b) High (1800 mm [5 ft]) dry bulb temperature (DBT)

(c) Medium (1200 mm [3 ft]) DBT

(d) Low (300 mm [1 ft]) DBT

(e) Floor (on the concrete slab) DBT

(f) Interior wet-bulb temperature (WBT)

(g) Exterior wet bulb temperature (WBT)[41]

(h) Exterior dry bulb temperature (DBT)[42]

The wet bulb temperatures were used to calculate the relative humidity with corresponding indoor and outdoor dry bulb temperatures. The globe thermometer gave the Mean Radiant Temperatures. All the measured data were stored on data-loggers and retrieved daily into a computer in the laboratory.

The other parts of the instruments, besides the main thermodac, included sensors and data loggers appropriately positioned under the schematic representation shown in Figure 27. Each sensor was positioned away direct solar radiation or the influence of radiant surfaces.

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[40] The sensors were located at the distances indicated above the finished floor level.

[41] Exterior value was measured only at one point for all houses.

[42] Ditto.

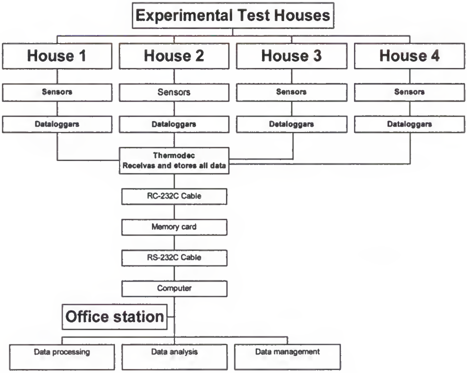

Figure 22: Schematic arrangement of the instruments' layout

The summary of the measured data is shown in Table 4. There were 8064 sets of data used in this analysis. The maximum dry-bulb temperature (DBT) in the low mass timber-GCI building without ceiling shows a build-up of heat to a point of 37.2°C (99°F) while outdoor temperature was 31.4°C (89°F). The high mass stone-GCI building is within the comfort zone, 24.5°C (76°F). The test houses with the GCI sheet roof are consistently above the comfort zone. Conditions in the high mass stone buildings appear to have comfortable temperatures.[43] The relative humidity ranged between 65% to 79% at dawn when air temperatures are at their daily lowest, and 17% to 31% in the afternoon when the air temperatures are their daily highest.

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[43] Comfortable temperatures are those that fall within the ASHRAE *Standard 55-92* comfort zone.

Results

Table 2: Summary of observed indoor temperature and humidity values

No Ceiling								
13th to 26th Jan 1997	Temperature		Maximum Humidity			Minimum Humidity		
	Maximum DBT	Minimum DBT	Wet bulb	Relative humidity	Humidity ratio	Wet bulb	Relative humidity	Humidity ratio
Timber wall, GCI roof	37.2	15.9	19.2	79%	0.009	12.0	31%	0.008
Timber wall, tile roof	34.0	16.5						
Stone wall, GCI roof	24.5	18.8						
Stone wall, tile roof	25.0	19.4						
Outside	31.4	14.1		86%			30%	
Slope Ceiling								
3rd to 16th Feb 1997	Temperature		Maximum Humidity			Minimum WBT		
	Maximum DBT	Minimum DBT	Wet bulb	Relative humidity	Humidity ratio	Wet bulb	Relative humidity	Humidity ratio
Timber wall, GCI roof	33.7	15.1	19.2	79%	0.009	12.0	31%	0.008
Timber wall, tile roof	32.0	15.4						
Stone wall, GCI roof	25.3	18.7						
Stone wall, tile roof	25.4	19.1						
Outside	32.8	12.1		78%			21%	
2/3 Ceiling								
21st Feb to 6th Mar 1997	Temperature		Maximum Humidity			Minimum WBT		
	Maximum DBT	Minimum DBT	Wet bulb	Relative humidity	Humidity ratio	Wet bulb	Relative humidity	Humidity ratio
Timber wall, GCI roof	34.1	16.4	18.0	81%	0.008	11.7	21%	0.007
Timber wall, tile roof	32.6	16.8						
Stone wall, GCI roof	26.9	20.4						
Stone wall, tile roof	25.4	19.1						
Outside	33.5	13.6		79%			19%	
Flat Ceiling								
10th to 23rd Mar 1997	Temperature		Maximum Humidity			Minimum WBT		
	Maximum DBT	Minimum DBT	Wet bulb	Relative humidity	Humidity ratio	Wet bulb	Relative humidity	Humidity ratio
Timber wall, GCI roof	32.7	19.6	14.8	65%	0.009	14.8	17%	0.005
Timber wall, tile roof	26.9	21.4						
Stone wall, GCI roof	28.2	22.4						
Stone wall, tile roof	27.8	22.0						
Outside	33.0	16.7		84%			25%	

Measured data from the test houses

Figure 23 shows a graphical representation of the field data summarized for an entire day in one of the low mass building (House 1). Figure 24 shows the representation for a high mass building (House 4). Generally, the low buildings were beyond comfort limits while the high mass buildings stayed within comfort limits.

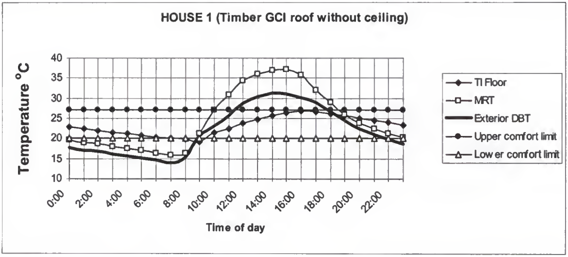

Figure 23: Measured Temperatures in a Low-mass House

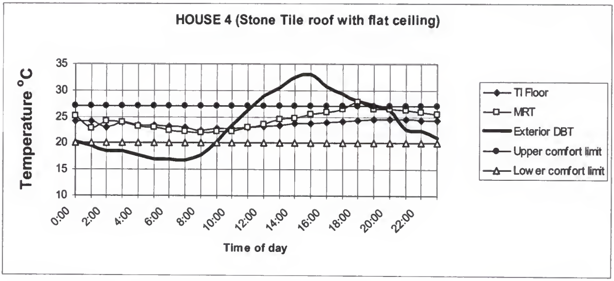

Figure 24: Measured Temperatures in a High-mass House

First, the low mass building (timber wall) closely followed the outdoor conditions. There was no significant moderation of temperatures. Second, the high mass (stone) buildings showed a clear time delay and temperature moderation. The conditions are firmly within the comfort zone. Third, floor temperatures are the most stable; they have the smallest amplitude from mean values. More results are in Appendix B.

Criteria for Evaluating the Experimental Data

Since the main theme of this research was the effect of thermal mass on comfort conditions (using indoor temperatures as an indicator of comfort), the main criterion chosen for evaluating the performance of the buildings was borrowed from previous experiments conducted by Givoni (1976, 1998a, 1998b). Basically, it meant examining indoor maximum and minimum air temperature and its reduction below the outdoor maximum.[44] The effect of the various ceiling configurations is fully analyzed later. At this stage, only the situations without ceiling and flat ceiling will be discussed.

This study also borrows the concepts of the thermal time constant (TTC),[45] re-developed by Givoni and Hoffman[46] from previous work by Bruckmayer[47] and Raychoudhury,[48] and diurnal heat capacity (DHC)[49] that was developed by Balcomb.[50]

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[44] Expressed mathematically: (Outdoor – Indoor maxima) = (Slope) x (Outdoor temperature swing) + (Intercept)

[45] TTC was defined as "the heat stored in the wall per unit of heat transmitted through it" (Givoni, 1976, pp. 435). TTC is a measure of the heat capacity.

[46] Givoni, B. and M. E. Hoffman. 1968. Effect of building materials on internal temperature. *Research Report for the Ministry of Housing*, Building Research Station, Technion, Haifa, April 1968.

[47] Cited by Givoni (1976, pp. 117).

[48] Raychaudhury, B. C. and N. K. D. Chaudhury. 1961. Thermal performance of dwelling in the tropics. *Indian Construction News*, December 1961, pp. 38-42. Cited by Givoni, 1976, pp. 117.

The patterns of indoor temperature are a measure of the DHC. Givoni[51] (1998b, pp. 149-183) discussed a mathematical model predicting the quantitative effect of DHC on the performance of direct gain and its application. The concept was carried here.

Effect of Thermal Mass on Temperatures in Experimental Buildings

Comparing the experiments by Givoni with the results of this study, there is a clear pattern that show that indoor maxima follow the pattern of outdoor temperature swings. Looking at indoor air temperatures in two main cases, the effect of thermal mass was observed under these two main headings: Without-Ceiling and with Flat-Ceiling.

The psychrometric chart represents the initial observation made previously. It can now be seen that thermal mass is clearly responsible for adjusting internal conditions to remain within the narrow ASHRAE comfort zone. Many studies, by Givoni,[52] Humphreys,[53,54] Nicol,[55] Tanabe[56,57], Leaman & Bordass[58] and Kwok[59], have

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[49] DHC determines the capacity of the interior thermal mass to absorb solar energy penetrating through the windows thus by-passing the modifying effect of the walls and the roof, and to release the absorbed heat back into the interior air during the night hours.

[50] Balcomb, J. Douglas. 1983. *Heat storage and distribution inside passive solar buildings*. Report LA9694. Los Alamos National Laboratory, New Mexico: Los Alamos.

[51] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. Van Nostrand Reinhold, New York. See Chapter 4: Passive Solar Heating Systems p149-183.

[52] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. New York: Van Nostrand Reinhold pp. 25.

[53] Humphreys, M. A. 1975. Field Studies of thermal comfort compared and applied. *Building Research Establishment*, Current Paper. CP 76/75, Garston, Watford, UK

[54] Humphreys, Reverend Michael A. 1976. Field Studies of thermal comfort compared and applied. *Building Services Engineer*, 44, pp. 5-27.

[55] Nicol, F., G. N. Jamy, O. Sykes, M. A. Humphreys, S. Roaf, and Hancock. 1994. *Thermal Comfort in Pakistan*. UK: Oxford Brookes University, School of Architecture.

[56] Tanabe, S. I., K. Kimura, and T. Hara. 1987. Thermal comfort requirements during the summer season in Japan. *ASHRAE Transactions* 93 (1): 564-577. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[57] Tanabe, S. I. 1988. Thermal Comfort in Japan. Waseda University, Tokyo, Japan.

demonstrated that people in many parts of the world are comfortable beyond the limits of ASHRAE Standard 55 and ISO 7730.

Figure 25 is a summary of the composite psychrometric chart that shows the measured indoor temperatures in the houses. The comfort zone as defined by ASHRAE and Givoni are superimposed. It can be clearly seen that high mass buildings are predominantly in the comfort zone. The low mass buildings tend to follow outdoor temperature trends and have shorter periods in the comfort zone.

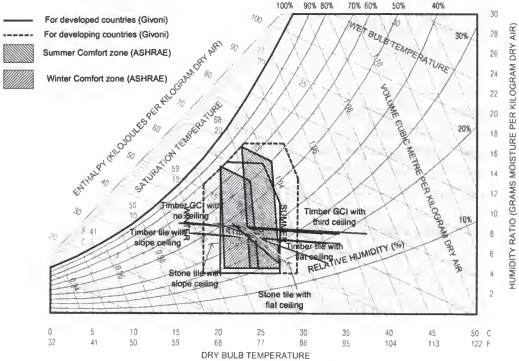

Figure 25: Measured conditions in the four houses on psychrometric chart

The psychrometric chart demonstrates that the direct application of the ASHRAE and ISO comfort zones without considering local factors, acclimatization and human experiences can lead to unnecessary air conditioning.

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[58] Leaman, Adrian and Bill Bordass. 1999. Productivity in buildings: the "killer" variables. *Building Research & Information* (1999) 27 (1), 4-19. London: E & FN Spon.

[59] Kwok, Alison G. 1998. Thermal Comfort In Tropical Classrooms in *ASHRAE Transactions* SF-98-7-5. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

Buildings Without Ceiling

Figure 26 shows the air temperature patterns in one of the houses during the measurement period of 13th to 26th January 1997. They also show the outdoor temperature patterns and daily averages. The indoor maximum temperatures follow similar patterns with outdoor temperatures. Humidity is highest at dawn when air temperature is least, and is least in the early afternoon when air temperature is highest.

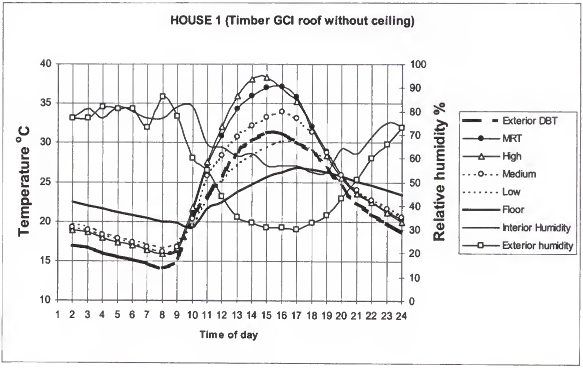

Figure 26: Outdoor and indoor temperature patterns in a house without ceiling

In the timber houses (low mass) peak indoor temperatures are actually above the peak outdoor temperatures because heat energy accumulates in the space. In the case of the stone houses, there is a considerable amount of moderating effect noticeable from the high thermal mass. The temperatures in the low mass buildings are about 4-5°C (7-9°F) above the peaks of the outdoor temperatures. In the high mass buildings, the temperatures are below by about 7°C (12°F). The floor temperature is consistently within comfort zone. Therefore, thermal mass appears to have lowered maximum temperature in the stone buildings to the comfort zone. Other results for the condition appear in Appendix B.

Buildings With Other Ceiling Configurations

In the second, third and fourth ceiling configuration of the houses, there was a clear pattern. The observed results are shown in Figures 27 and 28. The figures show daily indoor and outdoor temperature patterns. It should be noted once again that the pattern indoors followed the outdoors in the low mass buildings. In the high mass buildings, there was temperature moderation due to the effect of thermal mass and it was also noticeable that there was a time lag ranging several hours. In all these cases, the ventilation rates were about 0.5-air change per hour achieved through open eaves.

Floor temperatures remained consistently within the comfort zone except for a few times when there was an overheated point late in the afternoon hours. The observable point in the graphs is that the higher the thermal mass, the more the moderating effect on indoor maximum temperatures. As expected, temperatures were stratified in the room; cooler at the lower levels and hotter at higher levels. The low mass buildings closely followed outdoor conditions and did not offer much thermal storage. In one case when maximum outdoor temperature was over 33°C (91°F), the indoor maximum temperature in high mass building was 25.4°C (77.7°F), which is within the comfort zone. The humidity levels appear to be similar throughout the test period. The highest humidity is at dawn when air temperature is least; humidity is least in the early afternoon when air temperature is highest.

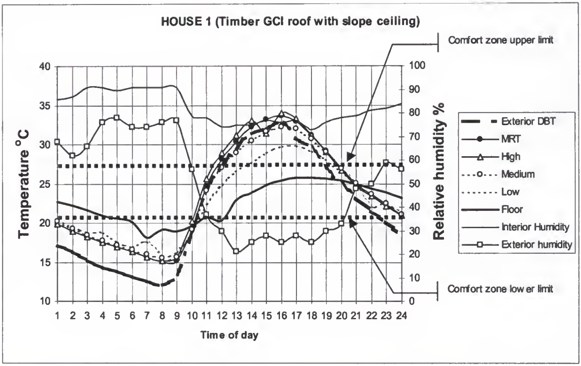

Figure 27: Patterns in House 1 (Timber GCI with slope ceiling)

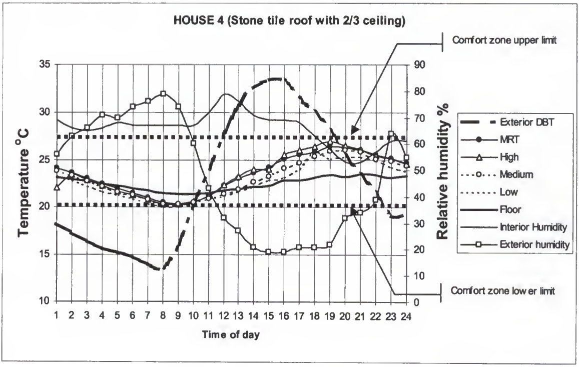

Figure 28: Patterns in House 4 (Stone tile with 2/3 ceiling)

Comparing Temperatures in all Houses Without Ceiling

The mean radiant temperature and outdoor temperature in the four houses are shown Figure 29. The mean radiant temperature (MRT) in House 1 (Timber GCI) exceeds the outdoor peak temperature by about 5°C (9°F) (5 K).[60] In House 2 (Timber tile), MRT exceeds outdoor peak temperature by 2 K. In House 3 (Stone GCI), MRT is within the comfort zone. It is below outdoor peak temperature by about 7 K. In House 4 (Stone tile) MRT is below outdoor peak temperature by about 9 K, i.e. 14 K below the House 1 in the same period. House 4 stayed within comfort limits most of the time.

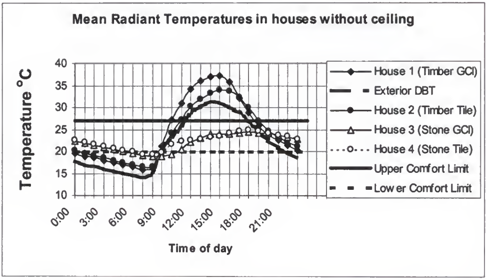

Figure 29: Mean radiant temperatures within all houses without ceiling

Other results related to this are in Appendix B

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[60] The unit usually used to describe temperature differences is the Kelvin (K). A difference of 1 K is equivalent to 1°C.

Comparing Temperatures in all Houses With Slope Ceiling

The mean radiant temperature (MRT) in House 1 (Timber GCI) closely follows outdoor temperatures and has a short time lag (Figure 30). In House 2 (Timber tile), MRT during the day follows the trend outdoors and has a time lag of 1.5 hours. In House 3 (Stone GCI), MRT is within the comfort zone and the flattening effects of thermal mass begin to show. Peak MRT is below peak outdoor temperature by about 7 K and the time lag is 4 hours. House 4 has MRT within the comfort zone. Peak values are different by about 7 K and the time lag is about 4.5 hours.

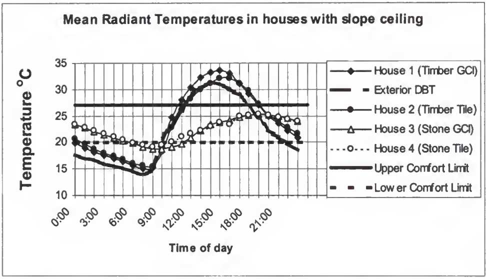

Figure 30: Mean radiant temperatures within all houses with slope ceiling

Comparing Temperatures in all Houses With 2/3 Ceiling

The mean radiant temperature (MRT) in House 1 (Timber GCI) closely follows outdoor temperatures and has no real time lag (Figure 31). In House 2 (Timber tile), MRT during the day follows the trend outdoors and has a time lag of 1.5 hours. In House 3 (Stone GCI), MRT is within the comfort zone and again the flattening effects of thermal mass show. Peak MRT is below peak outdoor temperature by about 8 K and a time lag of 4 hours. House 4 has MRT within the comfort zone. Peak values are different by about 8 K and the time lag is about 5 hours. In all cases, floor temperatures (high thermal mass) stay relatively stable within the comfort zone.

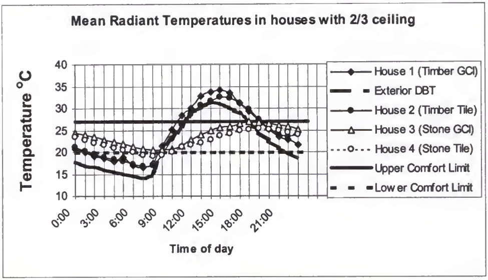

Figure 31: Mean radiant temperatures within all houses with 2/3 ceiling

Comparing Temperatures in all Houses With Flat Ceiling

The mean radiant temperature (MRT) in House 1 (Timber GCI) closely follows outdoor temperatures and has a short time lag (Figure 32). In House 2 (Timber tile), MRT during the day follows the trend outdoors and has a time lag of 1.5 hours. In House 3 (Stone GCI), MRT is within the comfort zone and again the flattening effects of thermal mass show. Peak MRT is below peak outdoor temperature by about 9 K and a time lag of 4 hours. House 4 has MRT within the comfort zone. Peak values are different by about 9 K and the time lag is about 4.5 hours. In all cases, floor temperatures (high thermal mass) stay relatively stable within the comfort zone. This trend has been observed in all the ceiling configurations.

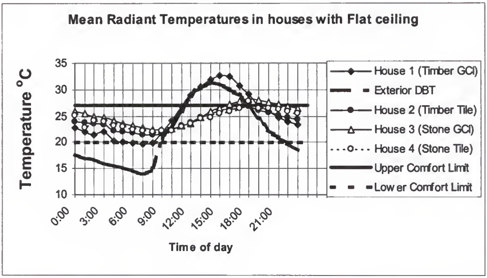

Figure 32: Mean radiant temperatures within all houses with flat ceiling

Observations Regarding the Effect of Ceiling Configurations

The arrangements above had a clearly observable pattern. The following issues were noted:

1. , Because the concrete floor slabs are a high thermal mass in contact with the ground, floor temperatures were within the comfort zone regardless of the ceiling arrangement. The measured temperatures show it.
2. In the light mass buildings with timber walls, mean radiant temperatures closely followed outdoor temperatures. At night they were radiant. The time lag in these light mass buildings was about 1.5 hours on average.
3. In the high mass buildings, there was a very clear drop in temperature because of the combination of thermal mass in the floor and walls.

4. Sensors for MRT and "Medium" thermometers were at the same level. By observing MRT, "Medium" and "High" temperatures, it is observable that MRT is generally lower than "High" air temperature but higher than "Medium" air temperature. This suggests that the roof is a more radiant element than the walls and that thermal mass should be located on the roof as well as the wall. Implicitly, the floor had a large stabilizing effect.

Taylor[61] et al. (2000, pp. 343) in Pretoria, South Africa observed that roof insulation altered indoor comfort conditions by about 4.5 K. This study showed that the ceiling configuration had some influence on mean radiant temperatures, and this suggests that they would affect thermal comfort of occupants of the space.

Analysis and Discussion

Formulae For Predicting Indoor Temperatures

A common feature noticed from the buildings with high thermal mass is the tendency of correlation between the indoor maximum temperatures and the outdoor air temperature patterns. Givoni also saw this observation consistently in several studies in California[62] and Israel[63]. It formed the basis for the development of a predictive formula for the expected indoor maximum temperatures, which were described fully in 1998[64].

---

[61] Taylor, P. B., E. H. Mathews, M. Kleingeld and G. W. Taljaard. 2000. The effect of ceiling insulation on indoor comfort. *Building and Environment* 35 (2000) 339-346. London: Elsevier Science Ltd.

[62] Givoni, Baruch. 1998a. Effectiveness Of Mass And Night Ventilation In Lowering Indoor Daytime Temperatures. Part I: 1993 experimental periods. *Energy and Buildings* 28 (1998) 25-32. Amsterdam: Elsevier Science Limited.

[63] Givoni, Baruch. 1976. *Man, Climate and Architecture*. Applied Science Publishers: London, UK. pp.137.

[64] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. New York: Van Nostrand Reinhold pp. 187-188.

His equation was used to predict for the same type of thermal mass used in this study and, while the patterns look similar, the differences between the predicted and the observed data are consistently about 2-3°C (4-6°F). The formula developed by Givoni was:

$$\mathbf{T_{max\text{-}in} = T_{max\text{-}out} - 0.31 \times (T_{max\text{-}out} - T_{min\text{-}out}) + 1.6}$$

Where:

$T_{max\text{-}in}$ = Indoor maximum temperature;

$T_{max\text{-}out}$ = Outdoor maximum temperature;

$T_{min\text{-}out}$ = Outdoor minimum temperature.

Data from this experiment were examined closely to see the relationships and phenomena that would offer useful explanations. Statistical analysis was conducted and there was a correlation (0.905) ($R^2 = 0.63$) between the drop of indoor maximum temperature below the outdoor maximum and the daily outdoor swing. The new formula was very close to that of Givoni. Full statistical summaries are in Appendix C.

The new regression analysis from this study for a high mass building was given by:

$$\mathbf{T_{max\text{-}in} = T_{max\text{-}out} - 0.488 \times (T_{max\text{-}out} - T_{min\text{-}out}) + 2.44}$$

(p-value = 0.01; $R^2 = 0.63$; Standard error ±0.68° C)

The two mathematical relationships (Givoni and this study) are close. The differences in the gradient (slope) and the "constant" can be explained by the fact that these studies have been done in different climates. The results of this study suggest that the new equation can be used for high thermal mass buildings comprising 200mm (8") thick stonewalls at equatorial high altitudes.

The new equation was applied to the published work by Givoni and generated the results in Figure 33. The figure shows the measured data and computed data side by side with the results using the equations from Givoni and this study. The prediction of indoor maximum temperatures using the equation of Givoni are close although consistently higher than the measured values by about 2-3°C (4-6°F). It appears that there is good prediction using the new formula derived from this experimental research.

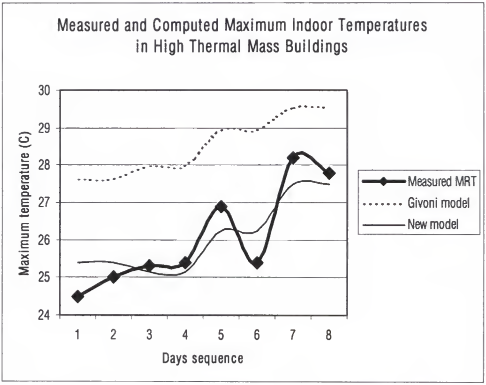

Figure 33: Measured and computed indoor temperatures in high mass building

After conducting a field study on thermal comfort in Thailand, Busch[65] noted: "Regression techniques are frequently employed in analyzing field study data because such studies provide a useful basis for interpreting results". This technique is incorporated into this study by using the format established by Givoni (1998a, pp. 30);

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[65] Busch, John F. 1995. Thermal comfort in Thai air conditioned and naturally ventilated offices. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century*. Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 114-121.

the above observations are expressed mathematically in the general form of the predictive formula:

(Outdoor – Indoor maxima) = k x (Outdoor daily temperature swing) + C

$$T_{\text{Outdoor max}} - T_{\text{Indoor max}} = k\,(T_{\text{Outdoor max}} - T_{\text{Outdoor min}}) + C$$

Where:

$T_{\text{Outdoor max}}$ = Outdoor maximum temperature in a particular day;

$T_{\text{Outdoor min}}$ = Outdoor minimum temperature;

$T_{\text{Indoor max}}$ = Indoor maximum temperature;

$T_{\text{Outdoor max}}$ = Outdoor maximum temperature;

k = Slope ratio depends on the amount of mass level;

C = Intercept

The two variables, slope (k) and intercept (C), represent the thermal characteristics of the building: thermal resistance, mass, shading, external color, and the nocturnal ventilation rate. The regression equations were in the format:

$$\mathbf{MRT = kx + C}$$

Where x is the temperature measurement at a given position. The regression equations that are shown later will follow this format. Temperatures within the high mass building correlate very highly (>0.900).

Table 3 shows that the low mass building offered little moderating effect. The mean radiant temperature correlated very highly (0.943) with outdoor air temperature. Table 4 shows that in the high mass building, they correlated poorly (0.512).

Table 5 shows the data from simple regression analysis for the correlation between mean radiant temperatures (MRT) and floor temperature (T_{floor}).

Table 3: Experimentally derived values of the k and C variables low-mass houses

Low mass	*Correlation with MRT*	*Slope (k)*	*Intercept (C)*	*Regression R^2*
High	0.977	0.925	1.558	0.955
Medium	0.978	1.073	-1.466	0.957
Low	0.962	1.314	-6.435	0.925
Floor	0.707*			
Exterior	0.943	0.837	5.365	0.890

Table 4: Experimentally derived values of the k and C variables in high-mass houses

High mass	*Correlation with MRT*	*Slope (k)*	*Intercept (C)*	*Regression R^2*
High	0.989	0.936	1.439	0.978
Medium	0.978	0.987	0.599	0.756
Low	0.932	1.078	-0.801	0.868
Floor	0.863	1.147	-2.259	0.746
Exterior	0.512*			

* Values had small correlations and were excluded from further analysis

Table 5: Data from simple regression analysis for MRT and floor temperatures

Ceiling Position	*Slope*	*Intercept*	*R^2*	*Equation*
No ceiling	1.89	-17.30	0.7406	$MRT = 1.89{*}T_{floor} - 17.30$
Slope ceiling	1.30	-5.42	0.7873	$MRT = 1.30{*}T_{floor} - 5.42$
2/3 ceiling	1.27	-5.05	0.7756	$MRT = 1.27{*}T_{floor} - 5.05$
Flat ceiling	1,96	-22.40	0.7307	$MRT = 1.96{*}T_{floor} -22.40$

Figure 34 shows normalized temperatures in Houses 4. The measure used in the stone-tile house is mean radiant temperature (MRT). It shows that floor temperatures are lower than MRT in the afternoon and early evening. Also, floor temperatures are higher than MRT from dawn through entire morning. These temperatures show the effect of thermal mass in moderating MRT. The normalized case for all the house types is shown in Figure 35. The stone-GCI house is generally warmer than the stone-tile house. Timber houses are much cooler at night suggesting that cooling and heating loads would increase as a result. Stone houses have thermal inertia that holds heat energy for long time lags.

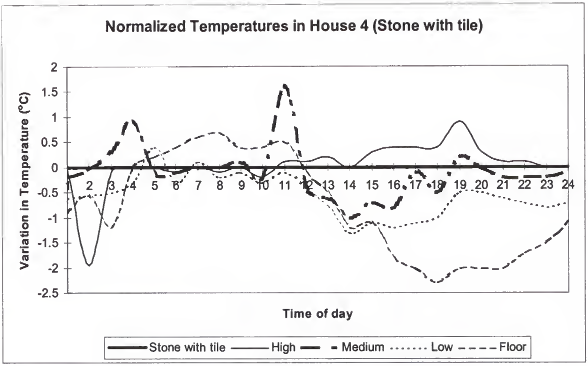

Figure 34: Normalized temperatures in House 4 (Stone wall with tile roof)

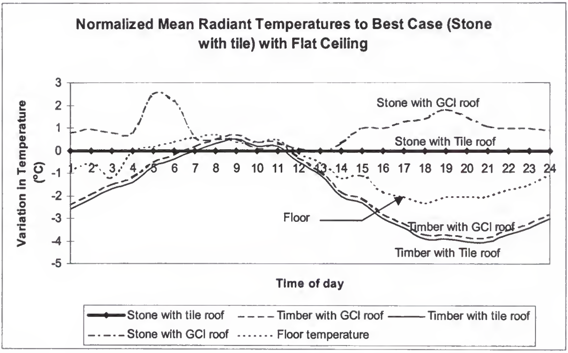

Figure 35: Normalized Mean Radiant Temperatures

An analysis of mean radiant temperatures measured in low mass buildings in this experimental study is plotted with exterior air temperature in Figure 36. The regression line of best fit is given by:

Mean Radiant Temperature = 0.837 (Exterior air temperature) + 5.365

Or:

$$\mathbf{MRT = 0.837T_{out} + 5.365}$$

192 observations; p-value = 6.09×10^{-93}; $R^2 = 0.8898$; Standard error = ±1.86° C.

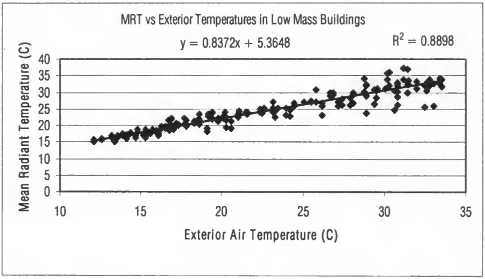

Figure 36: MRT vs. Exterior air temperatures in low mass buildings

Observed and computed values for a single day in one of the low mass buildings, shown in Figure 37, appear to have a close agreement. The mean radiant temperature (MRT) in the high-mass building as a function of time of day (x) is shown in Figure 38. It also shows the prediction of floor temperatures. The equations established were:

$$\mathbf{MRT = -0.0034x^3 + 0.1433x^2 - 1.5553x + 27.321} \qquad (R^2 = 0.939)$$

$$\mathbf{Floor\ Temperature = -0.001x^3 + 0.047x^2 - 0.5798x + 24.953} \qquad (R^2 = 0.8561)$$

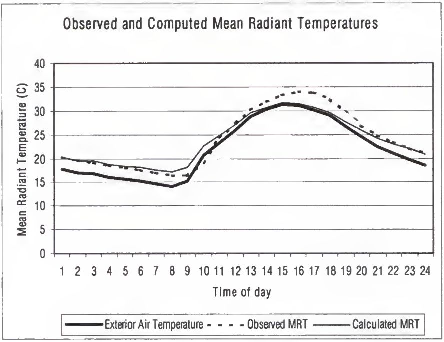

Figure 37: Observed and computed temperatures in low mass buildings

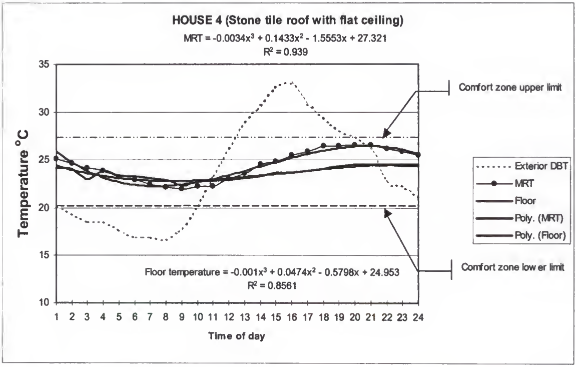

Figure 38: Predicted indoor mean radiant temperature and Floor temperature

Comparisons with Previous Studies

Several theoretical and experimental methods have been developed to predict the characteristics of internal temperatures. Givoni (1976, pp. 137) discussed some of these methods. For high thermal mass materials, he said: "the indoor temperature is closely related to the thickness of the walls and internal partitions". Mackey and Wright[66] used a theoretical method and developed algorithms to determine the decrement and time lag under natural external conditions, as functions of the thermal diffusivity and thickness of the building components, and of the cycle period. This method was limited for use here because it is only good for steady-state conditions (air conditioned spaces).

In Australia, Drysdale[67,68] suggested the formula:

$$T_{max\text{-}in} = T_{max\text{-}out} - 0.009W \text{ x } (T_{max\text{-}out} - 68)\ °F$$

Where:

$T_{max\text{-}in}$ = Indoor maximum temperature;

$T_{max\text{-}out}$ = Outdoor maximum temperature

W = average weight per unit area of the external walls (Ib/ft^2)

This formula assumes that the building is single storied and located in Australia (latitude 30°S). In India (latitude 20°N), Raychaudhury and Chaudhury[69] suggested this formula:

$$T_{max\text{-}in} = T_{max\text{-}out} - 0.004W \text{ x } (T_{max\text{-}out} - 60)\ °F$$

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[66] Mackey, C. O. and L.T. Wright. 1946. Periodic heat flow – composite walls or roofs. *Heat, Piping and Air Conditioning*, June 1946. Cited by Givoni, 1976, pp. 138.

[67] Drysdale, J. 1948.*Technical Study No. 27*, Comm. Exp. Bldg. Station, Australia. Cited by Givoni, 1976, pp. 141.

[68] Drysdale, J. 1961. Cooling the home, *Symposium on the Functional Effect of Buildings, Indian Concrete News*, CBRI, Roorkee, India, Nov. 1961, pp. 33-37. Cited by Givoni, 1976, pp. 141.

Where:

$T_{max\text{-}in}$ = Indoor maximum temperature;

$T_{max\text{-}out}$ = Outdoor maximum temperature

W = average weight of the whole structure, including roof, and the external walls, per unit area of the whole external surface (Ib/ft^2)

Much experimental research has been done and, as previously stated, according to Givoni (1998b, 187), the formula for a 200mm-thick mass wall is given as:

$$\mathbf{T_{max\text{-}in} = T_{max\text{-}out} - 0.31 \times (T_{max\text{-}out} - T_{min\text{-}out}) + 1.6}$$

Where:

$T_{max\text{-}in}$ = Indoor maximum temperature;

$T_{max\text{-}out}$ = Outdoor maximum temperature

$T_{min\text{-}out}$ = Outdoor minimum temperature

Results of the formulae determined in this study follow these previous works.

Predicting Thermal Sensation in Passive Solar Buildings

Humphreys[70] reviewed 36 field studies of thermal comfort in "free-running" passive solar buildings, totaling over 200,000 observations, and concluded that there is a relationship between neutral (preferred) temperatures and the mean monthly external air temperature. He found that:

Neutral Temperature = 0.534 (Average monthly exterior air temperature) + 11.9

Or, $T_n = 0.534T_{out} + 11.9$

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[69] Raychaudhury, B. C. and N. K. D. Chaudhury. 1961. Thermal performance of dwelling in the tropics. *Symposium on the Functional Efficiency of Buildings*, CBRI, November 1961, pp. 38-42. Cited by Givoni, 1976, pp. 138.

[70] Humphreys, Reverend Michael A. 1975. Field Studies of thermal comfort compared and applied. *Building Research Establishment*, Current Paper. CP 76/75, Garston, Watford, UK.

Outdoor temperatures are used to compute indoor neutral temperatures that 80% of a random sample of people will consider as the preferred or comfortable temperatures. The expected trend of Humphreys' equation needs to be validated for Nairobi, Kenya. The compilation of comfort temperatures is shown in the table below.

Table 6: Neutral temperatures based on Humphreys equation

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Observed Mean Temperature	18.0	18.6	19.4	19.1	17.9	16.3	15.4	15.8	17.1	18.6	18.1	18.0
Neutral Temperature	21.5	21.8	22.2	22.1	21.5	20.6	20.1	20.3	21.0	21.8	21.6	21.5

Table 6 implies that some heating is needed all year round. However, since the neutral (comfort) temperatures are higher than the observed mean temperatures by about 3°C, thermal comfort may be achieved by clothing and thermal mass for heat retention.

Effective Storage Capacity of Thermal Mass

Thermal capacity is defined as the amount of energy required to raise the temperature of a unit mass of a material by one degree; or

Thermal capacity = (specific heat) x (density) x (volume)

Ruud *et al.* (1990, pp. 820-829) discussed the concept called total heat capacity (THC), which is the maximum amount of thermal energy stored or released due to a uniform change in temperature (ΔT) of the material and is given by:

$$\mathrm{THC} = \rho c_p V \,\Delta T$$

Where ρ is density (kg/m^3), c_p the specific heat capacity, (kJ/(kg K)), V is the slab volume (m^3) and ΔT the change in temperature (K). This equation shows that the higher the density, specific capacity and volume the material has, the higher the THC. Givoni, (1998b, pp. 133) extended this discussion to another concept he called Thermal Time Constant (TTC),[71] which is the effective product of the thermal resistance and heat capacity of an envelope element. Its unit is time (hours). Balcomb (1987) devised the concept of diurnal heat capacity (DHC), which determines the capacity of a building's interior thermal mass to absorb solar energy.

The effect of high thermal mass and insulation on the indoor temperature average, swing, and time lag of a closed un-conditioned building, relative to the pattern of the ambient air temperature, depends on the order of the mass and insulation (Givoni, 1998b, pp. 133). Table 7 gives an example of TTC calculations of two insulated concrete walls of the same layers in different orders. Wall 1 had external insulation while Wall 2 had internal insulation. Thermal time constant can increase thermal inertia of building mass.

Table 7: Calculation of Thermal Time Constant of two walls (metric)

Wall 1						
Layer	Thickness (m)	Density (kg/m^3)	Resistance (K m/W)	Cumulative resistance	Heat Capacity	QR (Hours)
Exterior surface						0.03
Exterior plaster	0.020	1800	0.025	0.0425	414	0.35
Polystyrene	0.025	30	0.710	0.410	12	0.12
Concrete	0.100	2200	0.060	0.795	506	40.20
Interior plaster	0.010	1600	0.014	0.832	368	3.10
Wall's TTC						43.8
Wall 2						
Layer	Thickness (m)	Density (kg/m^3)	Resistance (Km/W)	Cumulative resistance	Heat Capacity	QR (Hours)
Exterior surface						0.03
Exterior plaster	0.020	1800	0.025	0.0425	414	0.35
Concrete	0.100	2200	0.060	0.085	506	4.3
Polystyrene	0.025	30	0.71	0.470	12	0.14
Interior plaster	0.010	1600	0.014	0.832	368	3.1
Wall's TTC						7.8

Source: Givoni, 1998b, pp. 136

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[71] Givoni, Baruch. 1976. *Man, Climate and Architecture.* London: Applied Science Publishers, pp. 117.

Figure 39 shows diurnal heat capacity (DHC) of various materials as a function of thickness of the elements. These DHC values show that the amount of stored heat per degree of temperature swing, in ascending order, from wood, sand, adobe, brick, stone and concrete.

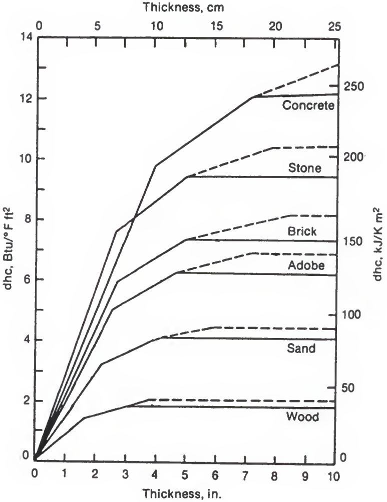

Figure 39: Diurnal Heat Capacity (DHC) of various materials
Source: Givoni, 1998b, pp. 138

A desired thermal mass material is one that has storage (absorptive) and re-radiative (emissive) properties that are combined to achieve long time lag and large moderating effects. Table 8 shows thermal properties of some common building materials. A proper mix of thermal conductivity,[72] heat capacity, density, emissivity[73] and absorptivity[74] can produce thermal mass highly useful in temperature moderation.

Table 8: Thermal heat capacities per square area of common building materials

Material	*Specific heat capacity (kJ/kg K)*	*Density kg/m^3*	*Thermal capacity per m^2 (kJ/ K)*
Stone (quarried)	0.800	1500	1200
Common brick	0.800	1970	1576
Ordinary concrete	0.653	2300	1502
Softwood (pine)	1.63	430	701
Water	4.180	998.2	4172

Source: ASHRAE, 1997, Table 4 Chapter 24 and Table 3 Chapter 36

The specific heat capacity of water (4.180 kJ/kg K) is over six times that of concrete (0.653 kJ/kg K). This means that water stores more than six times energy of the same weight of concrete. However, because of the massiveness (density) of concrete, it reduces this difference when thermal capacity is examined. Figure 40 shows thermal capacities per square area of some common building materials.

Time lag can be used to modify internal thermal conditions by shifting or delaying peak values diurnally, and thus create what Koenigsberger *et al.* called the *balancing-of-time*[75] in time lag.

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[72] Thermal conductivity is the rate of heat flow through unit surface area of a building material element of unit thickness, per unit temperature difference. Its unit is W/m.°C (Btu/hr.ft. °F).

[73] Emissivity is the capacity of a surface to emit long-wave radiation, relative to the radiation emitted by a "black body" (Givoni, 1998b, pp. 117).

[74] Absorptivity is the fraction of the striking radiation absorbed at the surface. For long wave radiation, emissivity = absorptivity. For solar radiation, generally emissivity absorptivity.

[75] Koenigsberger, Ingersoil, Mayhew, Szokolay. 1980. *Manual of Tropical Housing and Building Part 1: Climatic Design*. Longman, London.

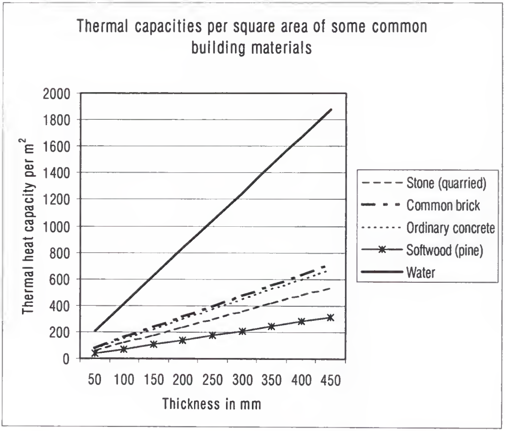

Figure 40: Thermal capacities per square area of some common building materials

Observed Time Lag and Decrement Factor

A recent study[76] shows that time lag and decrement factor are important characteristics to determine the heat storage capabilities of any material. Data from the test houses yielded the following observed time lag and decrement factors from Figure 41. The time lag was about 4.5 hours (from about 3:30 to 8:00 PM). The decrement factor, a measure of the moderating effect of thermal mass, was given by the quotient of the inside maximum temperature and outside maximum temperature.

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[76] Asan, H. 1998. Effects of wall's insulation thickness and position on time lag and decrement factor. *Energy and Buildings* 28 (1998) 299-305. Amsterdam: Elsevier Science Limited.

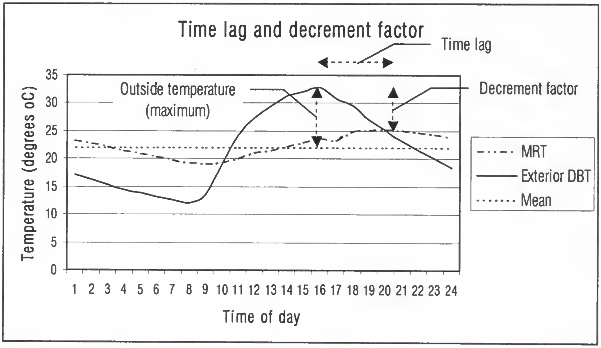

Figure 41: Definition of Time lag and Decrement Factor

Two quantities defined by the figure create a phase shift, ø, (time lag) and amplitude attenuation, μ, (decrement factor). Time lag and moderation effect (amplitude attenuation) increase with thickness, density and specific heat capacity of the material. They also increase with decreasing thermal conductivity. It was important to establish a formula for predicting from previous studies. By looking at much previously published literature, it became evident that the time lag, ø, and decrement factor, μ, can be calculated by expressions given by Hauser and Gertis[77]:

$$\text{Time lag, } \phi = s\sqrt{\frac{\rho \times c}{2 \times k \times \omega}}$$

$$\text{Decrement factor, } \mu = e^{-s\sqrt{\frac{\omega \times \rho \times c}{2 \times k}}}$$

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[77] Cited by Bansal, N. K., Gerd Hauser, Gernot Minke. 1994. *Passive Building Design: A Handbook of Climatic Control.* Amsterdam: Elsevier Science Limited, pp. 52.

Where:

s = thickness of the wall (m)

k = thermal conductivity (W/m K)

ρ = density of material (kg/m3)

c = specific heat capacity of material (J/kg K)

$$\omega = \frac{2 \times \pi}{24 \times 3600} (s^{-1})$$

Using the above equations to calculate time lag then comparing it with observed data from the experimental test houses, it appears the formula overestimates the time lag in both timber and stone. The calculated time lag for stone is higher the measured value by 27%; in timber it was overestimated by double. The results are shown in Figure 42. A suggested revision that corrects for the 27% overestimation in stone is:

$$\text{Time lag, } \phi = 0.73 \times s\sqrt{\frac{\rho \times c}{2 \times k \times \omega}} \quad \text{(Revised equation)}$$

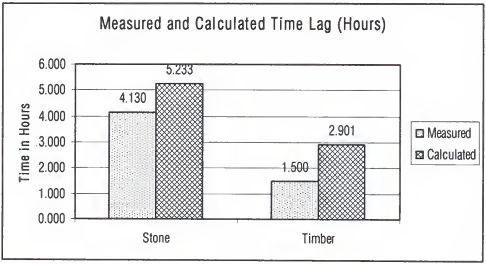

Figure 42: Measured and calculated time lag

Figure 43 shows lengths of time lag for a range of common building materials. Although wood has the greatest time lag, it has low thermal conductance. "This low conductance or high resistance prevents the middle of a mass of wood from participating efficiently in the storage of heat. Thus for a material to be a good heat storage medium it must have both high heat capacity and high conductance. For this reason water, steel, brick, and concrete, stone are some of the best choices."[78]

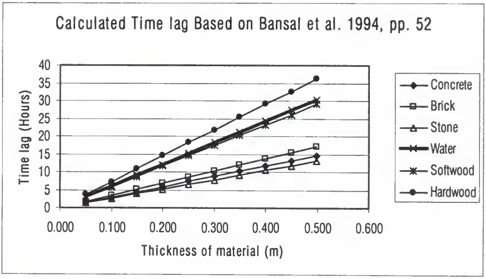

Figure 43: Range of time lag for various high mass materials

Characteristics of time lag from Olgyay's studies

Olgyay (1963, pp. 122-124) suggested the following material characteristics for a tropical humid region:

1. Heavyweight materials are advantageous when the diurnal range is large.
2. Zones of high diurnal variation need about a half-day time lag shift.

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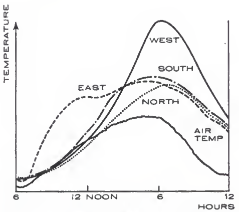
[78] Lechner, N. 1991. *Heating, Cooling, Lighting: Design Methods for Architects*. New York: John Wiley & Sons, pp. 125.

3. The heaviest load on the roof needs a shift of 11 – 12 hours.
4. East exposures need a minimum 12 to optimum 17-hour shift, or, no time lag to allow morning direct gains when temperatures are low indoors.
5. West exposures need a minimum lag of 5 hours to optimum 10hours.
6. North and south exposures need minimum 7 hours or optimum 10 hours.

Experimental observations were conducted on thermal behavior of building orientations at Princeton University's Architectural Laboratory. Figure 44 shows results of structures exposed to the cardinal directions. There is unequal heat distribution and high impact of the west exposure.



ROOM TEMPERATURE IN DIFFERENTLY ORIENTED HOUSES

Figure 44: Room temperatures in differently oriented houses
Source: Olgyay, 1994, pp. 705[79]

This translates into Figure 45, which shows that the east and west walls should be massive. The east wall may incorporate large openings and massive floor for direct solar radiation with some modifications from some specifics from the recommendations by Olgyay. The floor is a good thermal storage element for extreme climates (hot or cold) (Goswami *et al.*, 2000).

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[79] Olgyay, V. 1994. Optimum orientations in *Architectural Graphic Standards 9th Edition* by John Ray Hoke, Jr. (ed). American Institute of Architects, New York: John Wiley & Sons, Inc., pp. 705

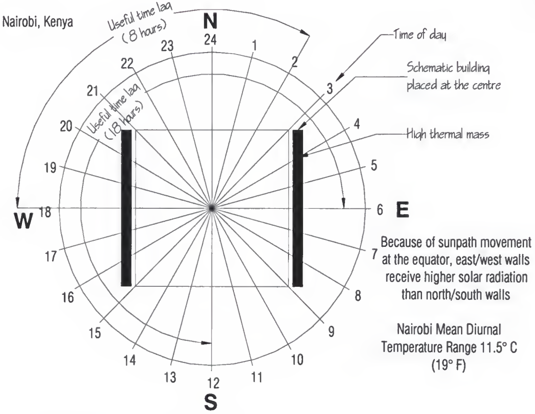
Nairobi, Kenya
Useful time lag (8 hours)
Useful time lag (18 hours)
N
W
E
S
24
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Time of day
Schematic building placed at the centre
High thermal mass
Because of sunpath movement at the equator, east/west walls receive higher solar radiation than north/south walls
Nairobi Mean Diurnal Temperature Range 11.5° C (19° F)

Figure 45: Desirable time lag characteristics on differently oriented surfaces

The elements most affected by direct solar gains are shown in Figure 46. The roof having the most horizontal component receives the highest solar radiation. The east and west walls also receive significant proportions of incident solar radiation. Since the north and south walls receive the least incident solar radiation, most window openings can be positioned there without serious adverse thermal comfort problems.

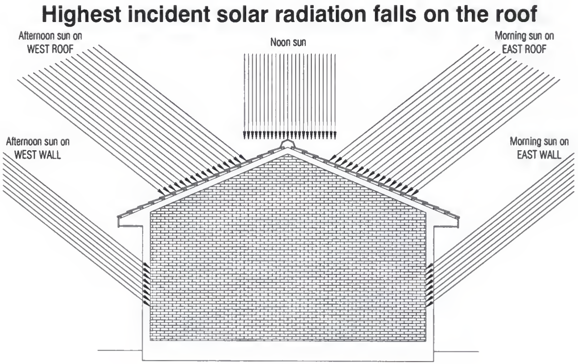
Highest incident solar radiation falls on the roof
Afternoon sun on WEST ROOF
Noon sun
Morning sun on EAST ROOF
Afternoon sun on WEST WALL
Morning sun on EAST WALL

Figure 46: Building elements that receive highest solar access at the equator

Effect of Ceilings on Indoor Comfort

Mean radiant temperature (MRT) expresses the effect of radiating surfaces that make a space, i.e. floors, walls and ceilings. Heat sensation in a space depends on the ambient air temperature, radiation from room surfaces internal heat gains and external heat gains. Mean radiant temperature in the ceiling configurations was compared to evaluate the effect of the ceiling on moderating air temperatures. From the summary of results that were made in Table 2, it was shown that there is a clear observable difference between mean radiant temperatures in buildings with no ceiling and those with ceilings. The mean radiant temperatures in houses without ceilings were consistently higher than those with ceilings by about 4°C (7°F). Statistically, conditions within the houses with ceilings were within 1° to 2°C of each other. This suggests that a barrier can reduce incoming solar heat gains through the roof before it is admitted within the structure.

The Florida Solar Energy Center conducted very extensive experimental research and simulations on the effect of radiant barriers on thermal performance of buildings (Chandra *et al.* 1986).[80] Chandra *et al.* compared the cooling and heating energy when materials with different thermal resistances are used in radiant barriers. The FSEC studies had ceilings in all conditions. Some were with radiant barriers, and some were without radiant barriers. These possibly created air space buffers that acted as insulators. Their study concluded that adding a radiant barrier outperformed ordinary insulated roofs. Radiant barriers are best applied to roofs on skin-load-dominated buildings in regions with high solar radiation.

While this study did not incorporate radiant barriers, there is a clear observable trend that shows that even a simple treatment of the ceiling surfaces has some effect on mean radiant temperatures within the space. These are discussed in the next section.

Effect of Floor Temperatures

Floor temperature has a significant influence on the mean radiant temperature in a room. Floor temperatures are themselves influenced by the presence of insulation, floor heating or incident solar radiation. Many studies have shown that when floors are too cold, people feel cold on their feet and they react by trying to raise the temperature of the room (ASHRAE 1997, pp. 8.12). This increases energy consumption.

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[80] Chandra, S., P. W. Fairey, and M. M. Houston. 1986. *Cooling with Ventilation*. Solar Energy Research Institute (SERI), Golden, Colorado. SERI/SP-273-2966, DE86010701. Cape Canaveral, FL: Florida Solar Energy Center (FSEC).

Olesen (1977a,[81] 1977b[82]) studied the influence of floor temperature on foot comfort. He did experimental studies and re-analyzed data from previous studies by Nevins (1958,[83] 1964,[84] 1966[85]). Olesen concluded that flooring material is very important for people with bare feet in buildings. He suggested that the range of temperature for concrete floors is 26 to 28.5° C.

Athienitis (1997, pp. 337-345)[86] investigated thermal performance of a passive solar building with floor radiant heating and found that sufficient thermal mass can ensure floor temperature limit remains 29° C.

Figure 47 shows the relationship between floor temperature and Percentage People Dissatisfied (PPD). Comfort was assessed using the ASHRAE Thermal Comfort[87] program with observed floor temperature as the input data. The program was adjusted to assume subjects who were in thermal neutrality so that the percentage of people dissatisfied is only related to thermal discomfort due to the thermal sensation on the feet.

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[81] Olesen, B. W. 1977a. Thermal comfort requirements for floors. Proceedings of Commissions B1, B2, E1 of the IIR, Belgrade, p337-43.

[82] Olesen, B. W. 1977b. Thermal comfort requirements for floors occupied by people with bare feet. *ASHRAE Transactions* 83 (2).

[83] Nevins, R. G. K. B. Michaels and A. M. Feyerherm. 1964. The effect of floor surface temperatures on comfort. Part I, College age males; Part II, College age females. *ASHRAE Transactions* 70:29.

[84] Nevins, R. G. and A. O. Flinner. 1958. Effect of heated-floor temperatures on comfort. *ASHRAE Transactions* 64:175.

[85] Nevins, R. G. F. H. Rohles, Jr., W. E. Springer, and A. M. Feyerherm. 1966. Temperature-humidity chart for thermal comfort of seated persons. *ASHRAE Transactions* 72 (1): 283.

[86] Athienitis, Andreas K. 1997. Investigation of thermal performance of a passive solar building with floor radiant heating. *Solar Energy* Vol. 61, No. 6, pp. 337-345 1997. Amsterdam: Elsevier Science Limited.

[87] Environmental Analytics (Berkeley, CA) developed a Thermal Comfort program for The American Society of Heating, Refrigeration, and Air-Conditioning Engineers. The program predicts human thermal response to the environment using several thermal comfort models, including PMV-PPD (Percentage Mean Vote-Percentage People Dissatisfied) and ET-DISC (Effective Temperature-Thermal Discomfort). This software calculates the predicted thermal comfort for a human at a point in space.

It shows that people will feel most comfortable when the floor is about 26° C (79° F). The data agree well with previous ASHRAE studies.[88]

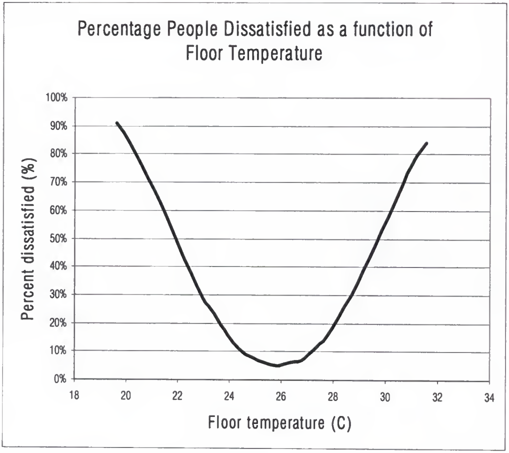

Figure 47: Percentage People Dissatisfied (PPD) as a function of Floor Temperature

The need to discuss comfort with respect to floor temperature is very important because the floor is a key thermal mass element. Floor temperature has psychological implications on the perception of comfort. ASHRAE *Standard 55-1992*[89] recommends a vertical air temperature difference between feet and heat of less than 3°C (5°F); a radiant temperature asymmetry from a cold wall or window less than 10°C (18°F); a radiant temperature asymmetry from a heated ceiling of less than 5°C (9°F); and a floor temperature range of 18°C to 29°C (64°F to 84°F). This study has values that appear to be within these limits.[90]

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[88] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition)*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. pp. 8.15.

[89] ASHRAE. 1992. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard 55-1992.* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

Effect of Insulation in Walls

This study dealt mainly with non-insulated solar buildings. However, it borrows some techniques from other studies with respect to insulation. There are numerous studies that have shown that insulation on the internal side of a space lowers the thermal mass effect of external walls (Givoni,[91] ECE,[92] Balcomb,[93] Balaras[94]). It reduces the energy required to heat up the building but can lead to overheating during the warm season.

Internal insulation impedes useful heat stored by thermal mass to be transmitted indoors or internal thermal conditions to be modified by the thermal mass. External insulation impedes solar radiation from causing rapid internal temperature swings but once heated the building retains the internal heat for a long period. Generally, thicker high mass walls stabilize internal temperatures better than thin low mass walls. The following three figures (48-50) show some wall assemblies.

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[90] Olesen, Bjarne W. 2000. Guidelines for comfort. *ASHRAE Journal* Vol. 42, No. 8, pp. 41-46. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[91] Givoni, Baruch. 1976. *Man, Climate and Architecture*. London: Applied Science Publishers p128.

[92] ECE: Economic Commission for Europe, Geneva. 1991. *Energy efficient design: a guide to energy efficiency and solar applications in building design*. ECE Energy series No. 9. New York: United Nations p55.

[93] Balcomb, J. Douglas. 1996. *Designing low-energy buildings: Passive solar strategies and Energy-10 Software*. Developed in collaboration with Passive Solar Industries Council, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and US Department of Energy (DOE) p23-25.

[94] Balaras, C.A. 1996. The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and Buildings*, 24 (1996) 1-10. Amsterdam: Elsevier Science Limited.

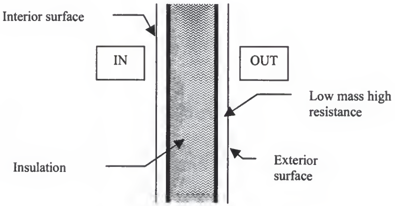

Figure 48: Construction detail showing thermal insulation inside wall

This arrangement is moderately effective because it lacks thermal inertia in its mass for providing sufficient moderating effect.

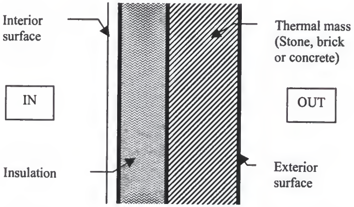

Figure 49: Construction detail showing thermal insulation inside the building Least effective in improving thermal mass effect

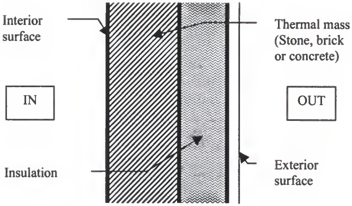

Figure 50: Construction detail showing thermal insulation outside the building
Most effective in improving thermal mass effect

Effect of Thermal Mass on Annual Energy

Balarus (1996, pp. 1-10)[95] presented a broad overview of computational methods on the role of thermal mass on cooling load in buildings. One of the findings presented was that locations with high diurnal temperature swing benefit the most from high thermal mass. A high mass test house was monitored in an environmental chamber under nighttime cooling operation, which found that nighttime cooling was more efficient than 24 h cooling by over 50% decrease in electric energy consumption (Kusuda, and Bean, 1987, pp. 1232-1240).[96] Goodwin and Catani[97] investigated the effect of mass on cooling loads and on insulation requirements for buildings in different climates. These studies may not offer direct insight fully because they were made in different climates. Ruud *et*

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[95] Balaras, C.A. 1996. The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and Buildings*, 24 (1996) 1-10. Amsterdam: Elsevier Science Limited.

[96] Kusuda, T. and J. Bean. 1987. Comparison of calculated hourly cooling load and indoor temperature with measured data for a high mass building tested in an environmental chamber. *ASHRAE Transactions* 87 (1981) 1232-1240. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[97] Goodwin, S. and M. Catani. 1979. The effect of mass on heating and cooling loads and on insulation requirements of buildings in different climates, *ASHRAE Transactions*, 85 (1) 869-884. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

al. (1990, pp. 820-829)[98] evaluated the effect of thermal mass on cooling energy through two experiments performed on the Independent Life Insurance building in Jacksonville, FL. and results showed an 18% reduction in cooling energy supplied during daytime. The study involved examining the reduction of energy demand in two experimental units with air conditioning. The passive strategy involved in the testing method was achieved by allowing nighttime pre-cooling of thermal mass. They used calculated and measured values of energy storage and further showed that even carpet on the floor significantly affected the effectiveness on energy demand.

Robertson (1986, pp. 387-417)[99] presented recommendations on how best to use thermal mass in the southwest United States for residential and small commercial buildings by strongly recommending dense and more conductive materials, such as high mass adobe materials.

Calculating annual cooling and heating energy provided another test for the effect of thickness of thermal mass. This was done using standard ASHRAE load calculation principles[100,101,102] and *Energy-10* program (Balcomb, 1996). High thermal mass was simulated for a standard building in the climate of Nairobi, Kenya. Results were observed under what Balcomb noted:

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[98] Ruud, M. D., J. W. Mitchell and S. A. Klein. 1990. Use of building thermal mass to offset cooling loads, *ASHRAE Transactions*, 96 (2): 820-828. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[99] Robertson, D. 1986. The performance of adobe and other thermal mass materials in residential buildings. *Passive Solar Journal*, 3 (1986) 387-417.

[100] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition)*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. Chapters 27 and 28.

[101] McQuiston, Faye C. and Jeffrey D. Spitler. 1992. *Cooling and Heating Load Calculation Manual.* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. pp. 8.1.

[102] Pedersen, Curtis O., Daniel E. Fisher, Jeffrey D. Spitler, Richard J. Liesen. 1998. *Cooling and Heating Load Calculation Principles*. American Society of Heating, Refrigerating and Air Conditioning Engineers Atlanta GA.

> For most materials, the effectiveness of thermal mass increases proportionally with thickness up to 4". After that the effectiveness doesn't increase significantly. For example, a two-inch mass floor over a plywood sub floor is about two thirds as effective as a four-inch thick floor. But increasing the thickness to six inches only improves storage by about 8%.[103]

When thermal mass absorbs heat, it becomes a radiator whether it is the floor, wall or roof. Different sizes of wall assemblies were tried in the simulation processes and they showed energy usage profiles shown in Figure 51 and 52. The effective thickness of material in controlling annual energy is approximately 100mm (4") and 200mm (8") thick. Annual heating energy reduced rapidly for thermal mass thickness between 25 and 200mm (1" to 8"). Beyond 300mm (12") there was no appreciable usefulness. It appears the physics behind the action is that extremely heavy materials (greater than 200mm thick) takes more energy for cooling. Generally, high thermal mass showed better reductions in annual heating energy.

These figures show that least annual cooling energy is achieved when thermal mass is about 100 to 200mm (4" to 8") thick. This is the same thickness when annual heating energy is optimum also.

There are other structural considerations that need to be taken into account such as transportation and total building-weight. These constraints are beyond the scope of this dissertation but can be evaluated. They appear potentially useful on the assumption that stone and concrete blocks are locally available to reduce the transport component of building costs.

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[103] Balcomb, J. Douglas. 1996. *Designing low-energy buildings: Passive solar strategies and Energy-10 Software*. Developed in collaboration with Passive Solar Industries Council, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and US Department of Energy (DOE) pp. 106.

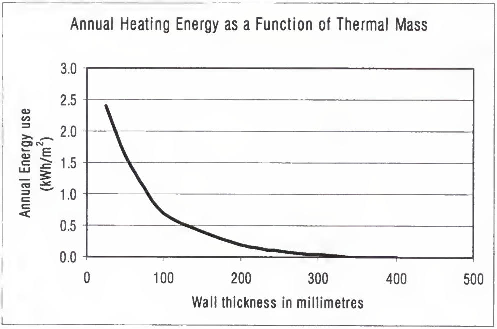

Figure 51: Annual heating energy as a function of thermal mass

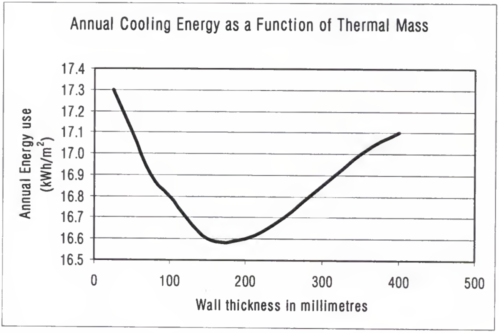

Figure 52: Annual cooling energy as a function of thermal mass

Conclusions from the Experimental Study

Thermal capacity is closely related to mass. Insulation (as needed) must be between the mass and the outside air. Heavy materials have time lag and moderating effects to internal temperature conditions. Givoni (1998a, 1998b) determined that the expected indoor maximum temperatures could be predicted from exterior temperature swing. A predictive formula for expected indoor maximum temperatures is:

$$\mathbf{T_{max\text{-}in} = T_{max\text{-}out} - 0.488 \times (T_{max\text{-}out} - T_{min\text{-}out}) + 2.44}$$

Where:

$T_{max\text{-}in}$ = Indoor maximum temperature;

$T_{max\text{-}out}$ = Outdoor maximum temperature

$T_{min\text{-}out}$ = Outdoor minimum temperature

An analysis of mean radiant temperatures measured in low mass buildings in this study showed a strong correlation ($r = 0.943$) with exterior air temperature. The regression line of best fit is given by:

Mean Radiant Temperature = 0.837 (Exterior air temperature) + 5.365

The following relationships were also established:

Table 9: Mean radiant temperatures (MRT) Equations

Ceiling	*Equation*
No ceiling	$MRT = 1.89 \cdot T_{floor} - 17.30$
Slope ceiling	$MRT = 1.30 \cdot T_{floor} - 5.42$
2/3 ceiling	$MRT = 1.27 \cdot T_{floor} - 5.05$
Flat ceiling	$MRT = 1.96 \cdot T_{floor} - 22.40$

Where T_{floor} is the temperature of the floor.

The mean radiant temperature (MRT) in the high-mass building as a function of time of day (x) is shown in Figure 38. It also shows the prediction of floor temperatures. The equations established were:

$$\mathbf{MRT = -0.0034x^3 + 0.1433x^2 - 1.5553x + 27.321} \qquad (R^2 = 0.939)$$

$$\mathbf{Floor\ Temperature = -0.001x^3 + 0.047x^2 - 0.5798x + 24.953} \qquad (R^2 = 0.8561)$$

The time lag for a 200mm thick heavy mass building material may be determined by an equation revised from the version published by Bansal *et al.* (1994, pp. 52) is:

$$\text{Time lag, } \phi = 0.73 \times s\sqrt{\frac{\rho \times c}{2 \times k \times \omega}} \text{ (Revised equation)}$$

Where:

s = thickness of the wall (m)

k = thermal conductivity (W/m K)

ρ = density of material (kg/m3)

c = specific heat capacity of material (J/kg K)

$$\omega = \frac{2 \times \pi}{24 \times 3600} \, (s^{-1})$$

However, there needs to be further study to specifically measure time lag and decrement factor for a wider variety of materials using a larger range of thickness to further validate this revision.

CHAPTER 3
EFFECT OF CLIMATE ON THERMAL MASS

Introduction

Climates directly affect architecture. Generally, hot climates require cooling, cool climates require heating, humid climates need dry air movement, and dry climates require moist air movement. This chapter discusses the climate of Nairobi, Kenya. Climate plays a key role in the effectiveness of thermal mass for temperature moderation. Most data in this chapter have been gathered by Kenya Meteorological Department[1] since 1955. The data are presented graphically, including building bio-climatic charts, to highlight key points relevant to this study.

Annually, Nairobi requires cooling 6% of the year, heating 60% of the year and it is within the comfort zone 34% of the year. An equatorial region has high solar radiation yet, as a recent study[2] shows, air temperature drops with altitude at a rate of approximately 5.9°C every 1000-metre rise (approximately 3.24°F every 1000-foot rise).

Another study[3] was done on the impediments and opportunities of bio-climatic building design techniques in Kenya. It suggested that agents and methods of promotion be developed to improve passive design systems. When faced with limited budgets, many developing countries more or less choose more critical national priorities such as health, agriculture, education and transport.

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[1] Kenya Meteorological Department. 1984. *Climatological Statistics for Kenya*. Dagoretti Corner, Ngong Road, Nairobi, Kenya, Ministry of Transport and Communications p60.

[2] Ogoli, David Mwale. 2000. An assessment method for the performance of passive solar buildings at equatorial high altitudes in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 827-828. James & James (Science Publishers) Ltd.

[3] Njuguna, Dafton G. 1997. Diffusion of Bio-climatic building design techniques in Kenya: Impediments and opportunities. *Habitat International* Vol. 21, No. 4 pp. 347-359, 1997. Amsterdam: Elsevier Science Limited.

Affordable housing is recognized as a means of attaining better productivity and social order. One way of improving shelter is by providing a low-cost indoor thermal environment, which is capable of acceptable levels of comfort, without a significant increase in commercial energy consumption (Njuguna, 1996, pp. 348).

A study in 1991 by Adebayo[4] drew attention to some aspects of urban climatology that are relevant to design in Nairobi. Other studies by Meffert[5] and Flatt[6] gave detailed climatic site analysis for integrating into urban planning of the city of Nairobi.

However, more research on passive solar designs applicable to the local climate is needed. Historically, government in response to external and internal influences has driven research and development in Kenya (Republic of Kenya, 1997b, pp. 174).

There are other forces that determine energy-usage. 75% of urban residential energy for cooking and space heating comes from wood (O'keefe *et al.* 1984)[7] and can be reduced if climate-conscious passive solar heating and natural cooling design strategies are implemented (UNHCS, 1984).[8,9] Studies on climate and design have been done in over 20 years and their importance continues to grow.[10,11,12,13,14]

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[4] Adebayo, Yinka R. 1991. On climatic reference points for some aspects of engineering design in Nairobi, Kenya. *Energy and Buildings* 15-16 (1990/91) 801-808. Amsterdam: Elsevier Science Limited.

[5] Meffert, Erich, E. 1991. The climate – site analysis in *Climate and human settlements: Integrating climate into urban planning and building design in Africa*, by Yinka R. Adebayo (ed). Nairobi: United Nations Environmental Programme, pp. 11-14.

[6] Flatt, Derrick. 1991. Cooling and ventilation in Kenya: Some comments in *Climate and human settlements: Integrating climate into urban planning and building design in Africa*, by Yinka R. Adebayo (ed). Nairobi: United Nations Environmental Programme, pp. 63-64.

[7] O'Keefe, P. (ed). 1984. *Energy and Development in Kenya*. Scandinavian Institute of African Studies, Uppsala.

Climate of Nairobi, Kenya

This chapter is more than just a basic study of the climate. There are three basic approaches. First, it is a presentation of the climatic data. Second, it is an explanation of the climatic data in terms of physical principles. Third, analyze benefits of climate to the improvement of the effect of thermal mass on temperature moderation. Temperature is important. Regarding temperature swing, Balcomb[15] said:

> A common problem in passive solar design is not providing enough mass in the building to store the solar gains. An effective way to determine if there is enough mass is to calculate the temperature swing on a clear mid-winter day under free-running conditions, that is without back-up heat. If the swing is not excessive, then there is sufficient mass, and adequate thermal comfort is assured. The temperature swing estimate is based on the diurnal heat capacity (DHC) method (Balcomb, 1987).

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[8] UNCHS: United Nations Centre for Human Settlement. 1984. Energy conservation in the in the construction and maintenance of buildings (1: Use of solar energy and natural cooling in the design of buildings in the developing countries. Report CHS/49/84/E. UNCHS, Nairobi.

[9] Scandinavian Institute of African Studies, Uppsala, Sweden. 1984. *Environment and Development in Africa 6: Wood, energy and Households: Perspectives on Rural Kenya* by Carolyn Barnes, Jean Ensringer and Phil O'Keefe (eds.). The Beijer Institute, The Royal Swedish Academy of Sciences, Stockholm, Sweden.

[10] United Nations. 1971. *Climate and Housing Design 1.* United Nations, New York.

[11] Koenigsberger, Ingersoil, Mayhew, Szokolay. 1974. *Manual of Tropical Housing and Building Part 1: Climatic Design.* London: Longman Limited.

[12] UNCHS: United Nations Centre for Human Settlement. 1990. *National design handbook prototype on passive solar heating and natural cooling of buildings.* Report CHS/182/89.E. UNCHS, Nairobi.

[13] Bansal, N. K., Gerd Hauser, Gernot Minke. 1994. *Passive Building Design: A Handbook of Climatic Control.* Amsterdam: Elsevier Science Limited.

[14] Banham, Reyner. 1969. *The Architecture of the Well-Tempered Environment.* Chicago, IL: The University of Chicago Press.

[15] Balcomb, J. Douglas. 1992. Passive solar building research in *Advances in Solar Energy: An Annual Review of Research and Development*, by Karl W. Boer (ed) Vol. 7 1992, pp. 239-282. Boulder, Colorado: American Solar Energy Society, Inc.

Balcomb outlined an analytical procedure in which the total heat absorbed in the building during the day is estimated by summing the effective heat storage potential of all the various materials in the building for a 24-hour periodic cycle of solar input.

In the following section, mean dry-bulb temperatures were taken at 9am and 3pm. Relative humidity was taken at 6am, 9am and 3pm. Mean daily wind speed was recorded using an anemometer mounted on a post with cups 2m (6' 7") above the ground. Monthly average rainfall was measured by a standard rain gauge. The collecting aperture was 127mm (5") diameter and set 300mm (1') above the ground. Daily sunshine hours were given for every month. Daily solar radiation was given for the hottest and coolest months.

Geographical Location

The city of Nairobi (population 1.83 million)[16] is a prominent African city, not just because it is the capital city of the Republic of Kenya (population 29 million),[17] but also because it is the largest city in eastern and central Africa. Kenya is bordered by Ethiopia on the north, Tanzania on the south, Uganda on the west, Sudan on the northwest, Somalia on the east, and Indian Ocean on the southeast.

The country is astride the equator and extends between latitudes 4.35°N and 4.47°S and longitudes 34°E and 42°E.[18] The size of the country is 582, 646 km^2 (224,960 sq. miles) roughly the size of the state of Texas or 2.4 times the size of the United Kingdom. Location of Nairobi, Kenya, is shown in Figure 53.

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[16] Census done by Kenya Bureau of Statistics 1999.

[17] Ibid.

[18] Ojany, F. F. and R. B. Ogendo. 1973. Kenya: *A Study of Physical and Human Geography*. Nairobi: Longman Kenya Limited pp. 1.

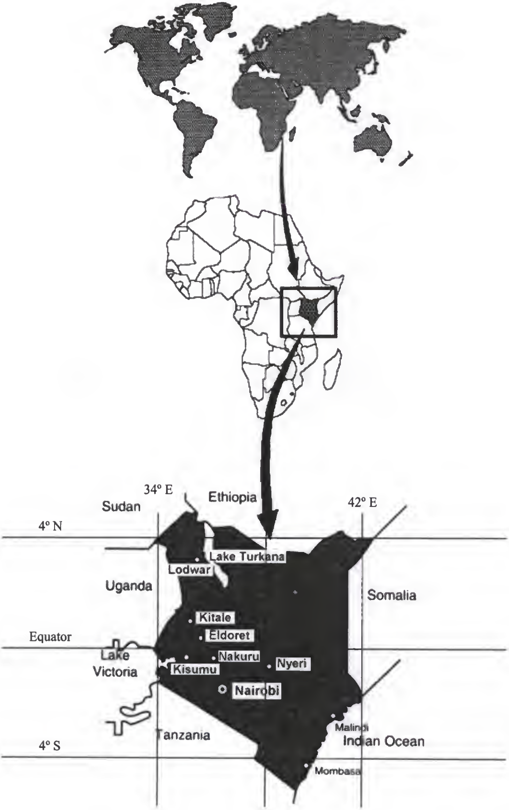

Figure 53: Location of NAIROBI, Kenya

Topography, vegetation, lakes and strong air movements that are driven by the monsoon winds across the Indian Ocean define climate in Kenya. This climate varies from cool temperate-like features (at high altitudes) to hot dry areas (in low altitudes).

Topography of Kenya

A typical section showing the topography of Kenya is summarized in Figure 54. Mombasa is at sea level. The highest point is Mt Kenya at an altitude of 5199m (17058 feet) above sea level. The rift valley is a major feature occurring in the central highlands. The ensuing climatic zones are affected by this topographical layout. Kenya experiences strong seasonal winds that are responsible for the rainy seasons. Most people live at altitudes between 1000 and 2500m (3048 and 8202 feet) above sea level.

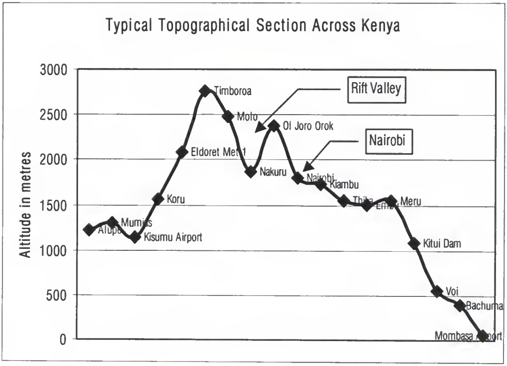

Figure 54: Typical topographical section across Kenya

As Adebayo (1991, pp. 801) noted, the climate of Nairobi is influenced by the interaction of altitude, three-dimensional human developments, other surface features, topography and vegetation. The altitude of Nairobi taken at Dagoretti Corner is about 1798m (5900 feet) above sea level. Altitudes of other places in Nairobi are: Kabete Observatory in the north is 1820m (5971 feet); Jomo Kenyatta International Airport in the east is 1624m (5327 feet); Wilson Airport in the south is 1683m (5525 feet); and, National Laboratories is 1737m (5700 feet). Nairobi's latitude is 1.3°S and the longitude is 36.75°E. Local time is three hours ahead of Greenwich Mean Time (GMT + 3 hours).

Air Temperature

Average diurnal temperature variation is about 13.5°C (25°F). The highest temperature occurs at about 4pm and the lowest temperature at about 6am (Figure 55). The temperature range is uniform throughout the year. The highest temperature coincides with the lowest humidity and the lowest temperature with the highest humidity. Average daily temperatures rise as high as 28.9°C (84°F) at 4pm in February and they reduce as low as 9.8°C (50°F) at 6am in July.

The annual mean maximum and minimum temperatures are 26.4°C (79.5°F) and 12.9°C (55.2°F) respectively (Figure 55). The annual mean temperature is 18.8°C (65.8°F). The extreme highest and lowest temperatures on record are 30.6°C (87°F) and 2.5°C (36.5°F) respectively. Freezing has never been recorded in Nairobi. Some studies (Ojany and Ogembo, 1971, pp. 66) have found that Eldama Ravine near Nakuru has recorded absolute minimum temperature of –3.3°C (26°F) while absolute maximum temperature of 41.8°C (107°F) has been recorded at Magadi on the rift valley floor.

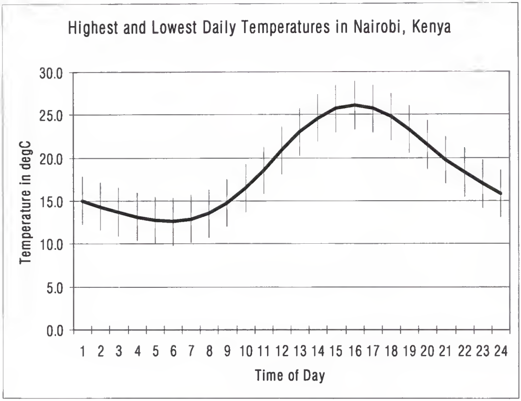

Figure 55: Average highest and lowest daily temperature in Nairobi, Kenya Based on data from Kenya Meteorological Department[19]

A more comprehensive study of the climate of Nairobi, Kenya is shown in Figures 56-58. The climatic conditions shown suggest that the highest and lowest produce a moderate climate. Figure 56 shows that there are not extremes. The dew point temperatures are shown in Figure 57. Because these temperatures are mostly below ambient air temperature, dew does not form except only at dawn. At dew point temperature the air reaches saturation, that is, it attains 100% relative humidity. Stein and Reynolds (2000, pp. 288) noted that this saturation point is "sometimes undesirable, as within walls or roofs, or on ceiling, air duct, or glass surfaces."

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[19] Kenya Meteorological Department. 1984. *Climatological Statistics for Kenya.* Dagoretti Corner, Ngong Road, Nairobi, Kenya, Ministry of Transport and Communications p60.

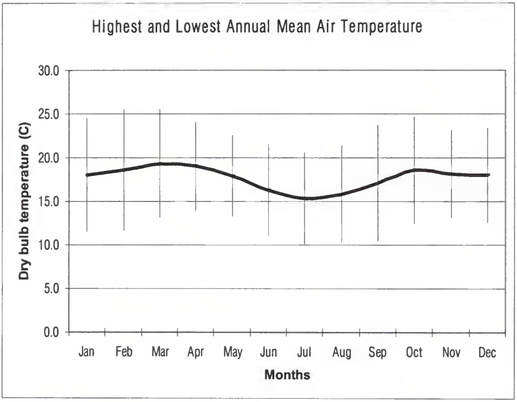

Figure 56: Highest and lowest annual mean air temperatures in Nairobi, Kenya Based on data from Kenya Meteorological Department[20]

The highest dew point temperatures occur around April. This period is generally rainy and cool. The lowest dew point temperatures occur in July, the coolest month.

Figure 58 shows the extreme temperatures ever observed since 1955 by Kenya Meteorological Department. It shows that ambient temperatures in Nairobi do not reach freezing point and they rarely exceed 30°C. They are close to the comfort zone and as was shown in Chapter 2, thermal mass can play a major role in bringing indoor conditions to the comfort zone.

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[20] Ibid. pp. 60.

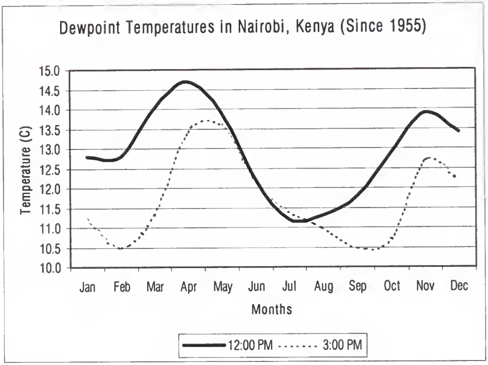

Figure 57: Dew-point temperature at noon and 3PM

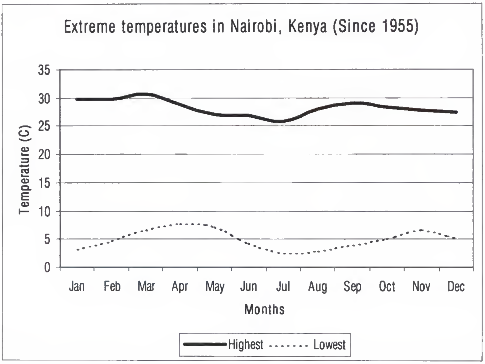

Figure 58: Extreme annual temperatures (since 1955)

Table 10: Cooling and Heating (Degree-days[21] and Degree-hours[22])

	Cooling degree days base 18.3°C	*Heating degree days base 18.3°C*	*Cooling degree hours base 27°C*	*Heating degree hours base 20°C*
Nairobi	392	215	511	5267

These data (Table 10) show that Nairobi has a mild climate with 392 cooling degree-days base 18.3°C (approximately 706 HDD65°F), and 215 heating degree-days base 18.3°C (approximately 385 CDD65°F). The general strategy for the climate of Nairobi is more heating than cooling. A complete year is made up of 8760 hours and the breakdown of these hours, typically for Nairobi, in Figure 59.

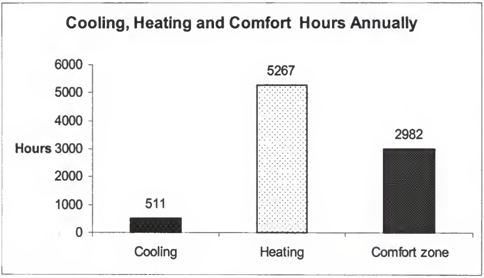

Figure 59: Number of hours for cooling, heating and comfort zone

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[21] A degree-day for a particular climate is the difference between a given base temperature and the mean temperature for each day. To derive heating degree-days (HDD) or cooling degree-days (CDD) for a given climate, the difference between each day's mean temperature and base temperature is calculated. When the mean equals the base temperature, no degree-days are recorded. When the mean temperature exceeds the base temperature it is CDD and when the mean temperature is less than the base temperature, it is HDD.

For example, assume that a day in Nairobi had a high of 29.0°C and a low of 17.6°C. Mean temperature is (29.0 + 17.6)/2 = 23.3°C. Therefore CDD18.3 = 23.3 – 18.3 = 5 cooling degree-days base 18.3°C.

[22] Degree-hours uses a similar concept as degree-days, except it uses hourly values and it gives more accurate estimates for energy calculation.

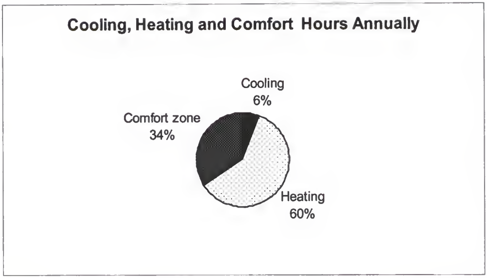

Figure 60: Ratio of cooling, heating and comfort zone hours

Figure 60 shows the ratio of cooling, heating and comfort zone hours for Nairobi, Kenya. Climatological statistics regularly collected since 1955 in over 90 meteorological stations[23] spread across the nation have been analyzed and they show that in Kenya altitude plays a key role in determining ambient climatic conditions. Temperature drops about 5.9°C for every 1000-metre rise (about 3.24°F for every 1000-foot rise). As stated earlier, the relationship between altitude and temperature is as follows:

$$\text{Mean Temperature } (^\circ\text{C}) = 28.7 - 0.00590A_{\text{metres}}$$

$$\text{Mean Temperature } (^\circ\text{F}) = 83.7 - 0.00324A_{\text{feet}}$$

Where A is the altitude above sea level in metres or feet (as indicated). As altitude increases there is a point at which temperature crosses into, and out of, the comfort zone. This is where thermal mass holds the potential of temperature moderation passively.

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[23] Kenya Meteorological Department. 1984. *Climatological Statistics for Kenya*. Dagoretti Corner, Ngong Road, Nairobi, Kenya, Ministry of Transport and Communications, Republic of Kenya.

Solar Radiation

Measured Solar Radiation

Measured daily solar radiation and daily sunshine hours are shown in Figures 61-62. The instantaneous solar radiation for Nairobi is 317,394 W/m^2 (100,600 Btu/h ft^2). February receives the highest monthly radiation, and July the least.

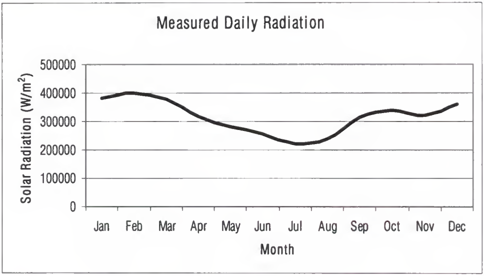

Figure 61: Measured daily radiation on a horizontal surface

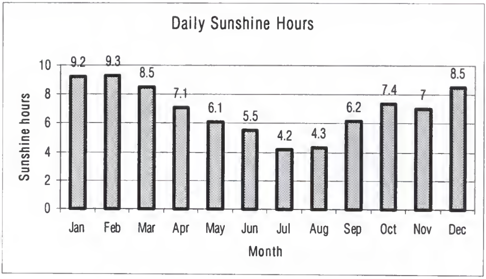

Figure 62: Measured Daily Sunshine Hours

Table 11 shows a summary of sunshine hours. Annual mean daily sunshine hours are 7.7 hours. Annual maximum sunshine hours occur in January (11.0 hours) and minimum sunshine hours in July (4.4 hours), when it is most cloudy.

Table 11: Measured Daily Sunshine Hours in Nairobi, Kenya

	Hours of sunshine	*Month*
Maximum mean	11.0	January
Minimum mean	4.4	July
Mean	7.7	Annual

Source: Kenya Meteorological Department.[24]

Calculated Solar Radiation

The design of passive solar buildings requires a thorough understanding of solar angles, for the placement of thermal mass, windows and shading devices. The following is a discussion on the mathematical relationships between the sun and earth movement. They are based on algorithms from (ASHRAE, 1997[25]; ASHRAE, 1999[26]; Goswami *et al.* 2000[27]). Figure 63 shows the definitions and relationships of various solar angles used in the calculations.

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[24] Ibid. pp. 60.

[25] ASHRAE. 1997. *Handbook of Fundamentals (SI Edition).* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. Chapter 29: Fenestration.

[26] ASHRAE. 1999. *Handbook of HVAC Applications (SI Edition).* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. Chapter 32: Solar energy use.

[27] Goswami, D. Y, F. Kreith, J. F. Kreider. 2000. *Principles of Solar Engineering*. Philadelphia, PA: Taylor & Francis, Chapter 2: Fundamentals of Solar Radiation.

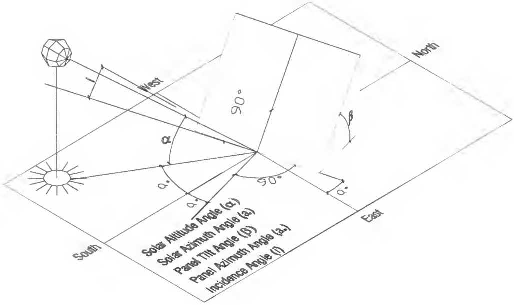

Figure 63: Definitions of solar angles

The figure above is used to determine all solar angles. The symbols used are:

1. α = Solar Altitude angle
2. a_s = Solar Azimuth angle
3. δ_s = Solar Declination angle
4. L = Latitude angle
5. h_s = Solar Hour angle
6. h_{sr} = Sunrise Hour
7. h_{ss} = Sunset Hour
8. n = Day Number beginning with January 1 being $n = 1$

For Nairobi, Latitude L = 1.3°S, and Longitude l_{local} = 36.75°E.

The solar declination angle δ_s $= 23.45° \sin\left[\frac{360(284+n)}{365}\right]$ (1)

The solar altitude angle is given by:

$$\sin\alpha \quad = \sin L \sin\delta_s + \cos L \cos\delta_s \cos h_s \tag{2}$$

The solar azimuth angle is given by: $\sin\ a_s \ = \dfrac{\cos\delta_s \sin h_s}{\cos\alpha}$ (3)

At solar noon, $h_s = 0$; therefore, $\alpha = 90 - |L - \delta_s|$, and $a_s = 0$. Sunrise and sunset times can be estimated by finding the hour angle for $\alpha = 0$. Substituting $\alpha = 0$ in equation 2 gives the hour angles for sunrise (h_{sr}) and sunset (h_{ss}) as:

$$h_{sr} \text{ or } h_{ss} \quad = \pm\cos^{-1}\left[-\tan L.\tan\delta_s\right] \tag{5}$$

Goswami *et al.* (2000, pp. 29) emphasize that equation 5 is "based on the center of the sun being at the horizon. In practice, sunrise and sunset are defined as the times when the upper limb of the sun is on the horizon. Because the radius of the sun is 16', the sunrise would occur when α = -16'. Also, at lower solar elevations, the sun will appear on the horizon when it is actually 34' below the horizon. Therefore, for apparent sunrise or sunset, α = -50'".

The Equation of Time, ET, is given by:

$$\text{ET} \quad = 9.87\sin 2B - 7.53\cos B - 1.5\sin B \text{ min} \tag{6}$$

Where $$\text{B} \quad = \frac{360}{364}(n - 81) \tag{7}$$

Nairobi, Kenya, is in the East African Standard Time zone, where $l_{st} = 30°$ E. The solar angles above are for local solar time, which differs from the local standard time. The relationship between the local solar time and the local standard time (LST) is:

LST = Solar Time - ET - (l_{st} - l_{local}). 4 minutes/degree. (8)

The amount of solar radiation falling on a surface normal to the rays of the sun outside the atmosphere of the earth (extra-terrestrial) at mean Earth-sun distance is called the Solar Constant, I_o. Measurements indicate this constant as 1367 W/m^2.[28,29] The amount of solar radiation, (I), at a point on the earth is given by:

$$I \quad = I_o\{1 + 0.034\cos(360n/365.25) \tag{9}$$

As solar radiation I travels through the atmosphere, it is attenuated due to absorption and scattering. According to Bouger's law and the work of Threlkeld and Jordon,[30] the beam normal solar radiation, $I_{b,N}$, for a solar altitude angle is given by:

$$I_{b,N}, \quad = C_n\, I e^{-k/\sin\alpha} \tag{10}$$

Where C_n is a parameter called clearness number and k is the local extinction coefficient of the atmosphere. The total instantaneous solar radiation on a horizontal surface, $I_{c,h}$, is the sum of the direct solar radiation, $I_{b,h}$, and the sky diffuse radiation, $I_{d,h}$,:

$$I_{c,h}, \quad = C_n\, I e^{-k/\sin\alpha}(\mathrm{C} + \sin\alpha) \tag{11}$$

Solar radiation (I_c) on a tilted surface having a tilt angle of β from the horizontal and an azimuth angle of a_w (assumed + west of south) is the sum of the components of beam $(I_{b,c})$ sky diffuse $(I_{d,c})$ and ground reflected solar radiation ($I_{r,c}$). Therefore:

$$I_c \quad = I_{b,c} + I_{d,c} + I_{r,c} \tag{12}$$

If i is the angle of incidence of the beam radiation on the tilted surface, then:

$$I_{b,c} \quad = I_{b,N} \cos i. \tag{13}$$

From geometry it can be proved that:

$$\cos i \quad = \cos\alpha \cos(a_s - a_w) \sin\beta + \sin\alpha \cos\beta \tag{14}$$

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[28] ASHRAE. 1999. *Handbook of HVAC Applications (SI Edition)*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. pp. 32.1.

[29] Goswami, D. Y, F. Kreith, J. F. Kreider. 2000. *Principles of Solar Engineering*. Philadelphia, PA: Taylor & Francis, pp. 41.

[30] Threlkeld, J. L. and R. C. Jordan. 1958. Direct radiation available on clear days. *ASHRAE Transactions* 64: 45. The American Society of Heating Refrigerating, and Air-conditioning Engineers Inc. (ASHRAE), Atlanta, GA.

The diffuse radiation on a surface ($I_{d,c}$) is obtained by multiplying the sky diffuse radiation on a horizontal surface ($I_{d,c}$) by the view factor between the sky and the surface:

$$I_{d,c} \quad = I_{d,h}\,(1 + \cos\beta)/2 = CI_{b,N}\,(1 + \cos\beta)/2 = CI_{b,N})\cos^2(\beta/2) \qquad (15)$$

The ground reflected solar radiation could be found from the total solar radiation incident on a horizontal surface and the ground reflectance ρ as:

$$I_{r,c} = I_h\,\rho \qquad (16)$$

The part of I_r intercepted by the tilted surface can be found by:

$$(I_{d,c}) = \rho I_h\,(1 - \cos\beta)/2 = \rho I_h \sin^2(\beta/2) = \rho I_{b,N}\,(\sin\alpha + C)\sin^2(\beta/2) \qquad (17)$$

For ordinary ground or grass, ρ is approximately 0.2 and for snow covered ground it can be taken as approximately 0.8 (Goswami, *et al.*, 2000, pp. 48). Figures 64-68 show the relative solar radiation on surfaces oriented differently. The amount of solar radiation flux has been calculated using algorithms in the discussion above.

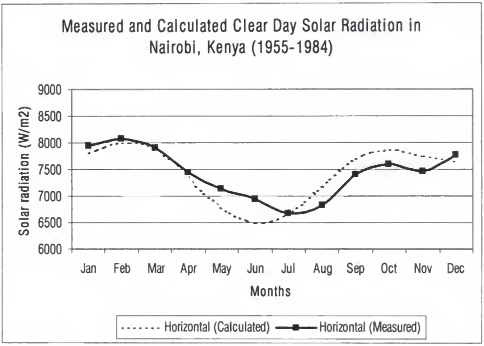

Figure 64: Measured and calculated solar radiation compared

Figure 65 shows that the horizontal surface receives as much as four times the radiation on east or west-facing vertical surface, and eight times as much as a north or south-facing vertical surface. The east and west facades have the same amount of radiation. The north receives higher radiation than the south from March to September (sun in northern hemisphere), and lesser radiation from September to March (sun in southern hemisphere).

The horizontal surface receives the highest solar radiation at mid-day. The E & SE and W & SW receive the next highest solar radiation in the morning and afternoon respectively. Daily, the S receives about half the amount on the horizontal surface. The N surface receives the least incident solar radiation. Figure 66 gives the relative amounts of solar radiation flux incident on building elements in various orientations.

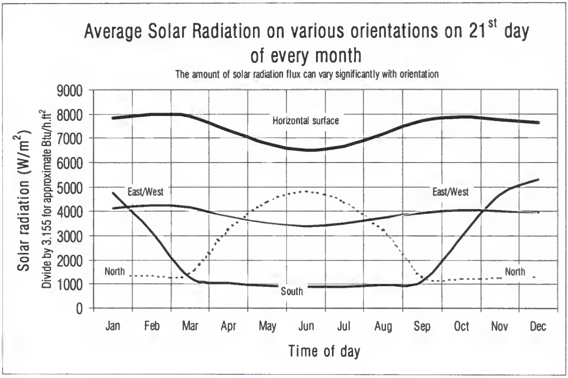

Figure 65: Average solar radiation on 21st day of every month

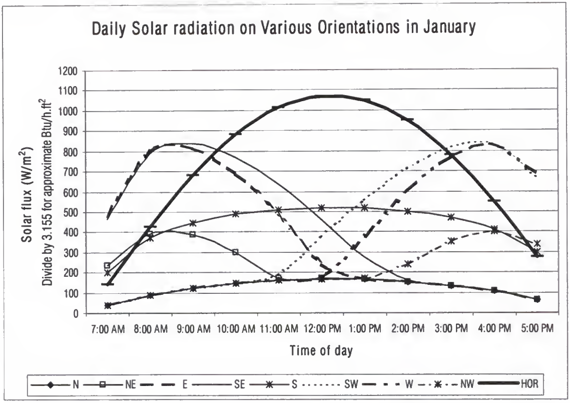

Figure 66: Daily solar radiation on vertical surfaces in January

Figure 66 raises an important question regarding the relationship between the solar radiation and solar altitude angle.

Graphically representing solar radiation data as a function of solar altitude angle in Figure 67 reveals several mathematical relationships. This shows the variability of available solar radiation at the equator regardless of altitude.

The amount of solar radiation on the horizontal rises and falls steeply from sunrise-to-noon and from noon-to-sunset. Solar radiation on the horizontal surface varies directly proportional with the solar altitude angle.

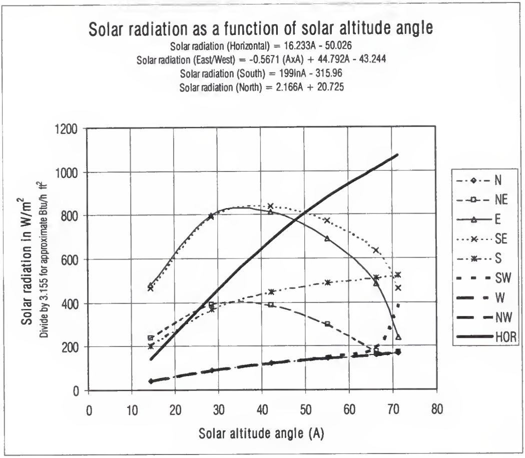

Figure 67: Solar radiation as a function of altitude angle
Computed using algorithms found in ASHRAE 1999[31] and Goswami *et al.* 2000[32]

Daily solar angles and reveals how solar altitude angles vary with solar azimuth angles. Figures 67 shows the equations the best fit their relationship. For solar radiation in W/m^2, the following were established:

Solar radiation (Horizontal) = 16.233A – 50.026

Solar radiation (East/West) = $-0.5671A^2 + 44.79A - 43.244$

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[31] ASHRAE. 1999. *Handbook of HVAC Applications (SI Edition)*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. Chapter 32.

[32] Goswami, D. Y, F. Kreith, J. F. Kreider. 2000. *Principles of Solar Engineering*. Philadelphia, PA: Taylor & Francis.

Solar radiation (South) = 199(Log A) – 315.96

Solar radiation (North) = 2.166A + 20.725

In the above expressions, A is the solar altitude angle in degrees. The horizontal element receives a rapid amount of solar radiation as the solar angles increase.

Figure 68 demonstrates that solar altitude angles are highest at noon and least at sunrise and sunset. Vice versa, solar azimuth angles are least at noon and highest at sunrise and sunset. At the equator, the highest solar altitude angle is about 69°, which occurs at solar noon.

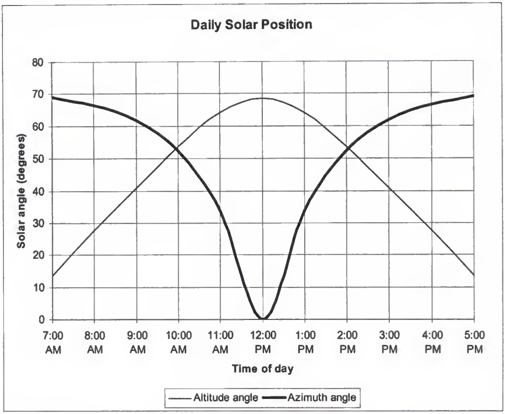

Figure 68: Solar altitude and Solar azimuth angles

Humidity

The amount of humidity is highest at dawn and least in mid-afternoon. The dry-bulb and coincident wet bulb readings are shown in Figure 69. Throughout the year there the air usually does not get completely moist or saturated (100% relative humidity) because the dry-bulb and wet-bulb temperatures do not get equal.

January and July are the extreme months. The driest conditions do not usually fall below 30%, which would be considered uncomfortable by 80% of the populations.

Elovitz (1999, pp84-90) discussed how moisture affects building materials and processes. He put into perspective the effects of what humidity does and why. Low mass and/or loose fabrics absorb more moisture and take longer to stabilize, while massive materials absorb less moisture and therefore tend to stabilize faster.

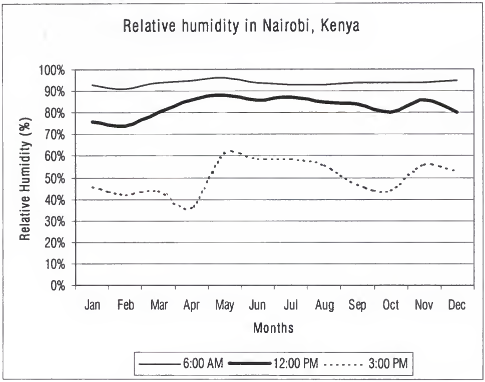

Figure 69: Relative humidity at 6AM, Noon, and 3PM

Rainfall

It has been observed that terrain considerably influences rainfall in Nairobi area.[33] The climate of Nairobi can be divided into two rain seasons: wet and dry.[34] The longs rain occur from April to May and the short rains from October to December. The mean monthly rainfall is shown in Figure 70. The highest rainfall comes in April (211 mm) and the least amount in July (19 mm). The mean annual rainfall is 1049 mm.

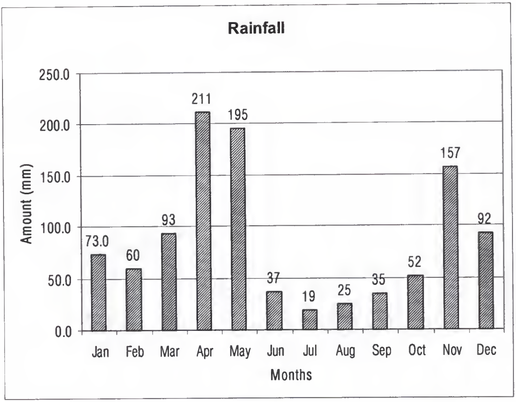

Figure 70: Rainfall patterns in Nairobi, Kenya
Based on data from Kenya Meteorological Department[35]

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[33] Nieuwolt, S. 1980. *Interpolation of rainfall in the Nairobi area, Res. Report No. 8/80*, East African Institute for Meterological Training and Research, 1980.

[34] Kenya Meteorological Department. 1967. *The climates of Nairobi, Pamphlet No. 2*. East African Meterological Department now Kenya Meteorological Department at Dagoretti Corner, Ngong Road, Nairobi, Kenya, Ministry of Transport and Communications.

Psychrometric Analysis of the Climate of Nairobi, Kenya

The following discussion stems from the need to make a building bio-climatic analysis using the psychrometric chart. A survey done comprising architects, engineers, policy-makers and other related professionals in Kenya revealed that 95% of the respondents favor more climate-responsive design to current architectural training at Kenyan Universities (Njuguna, 1996, pp. 356). Figure 71 shows psychrometric chart processes that define climate-conditioning processes. This will determine the applicability of usage of thermal mass.

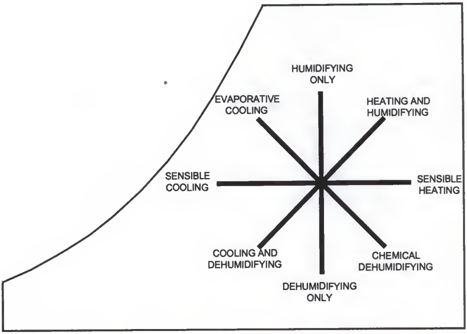

Figure 71: Psychrometric chart defining climate-conditioning processes
Source: Milne and Givoni, 1979, pp. 113.[36]

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[35] Kenya Meteorological Department. 1984. *Climatological Statistics for Kenya*. Dagoretti Corner, Ngong Road, Nairobi, Kenya, Ministry of Transport and Communications pp. 60.

[36] Milne, Murray and Baruch Givoni. 1979. Architectural design based on climate in: Donald Watson (ed), *Energy conservation through building design* chapter 6. New York: McGraw-Hill pp. 95-113.

The definitions of climatic zones are somewhat arbitrary; they are either heating, cooling or mixed climates.[37] The psychrometric profiles below (Figure 72-74) depict the climate of Nairobi as moderate or mixed;[38] it is not cooling warm and humid climate[39] as is most often mistakenly assumed to be. Nairobi has slightly more heating[40] degree-days than cooling degree-days.

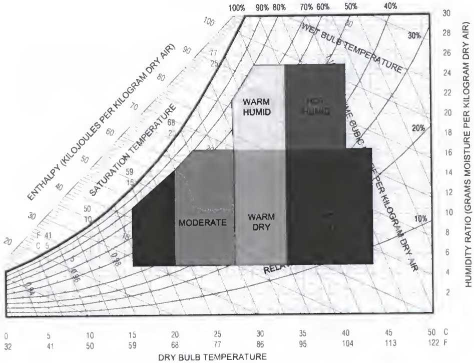

Figure 72: Climatic zones as defined on the psychrometric chart

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[37] Lstiburek, J. and J. Carmody. 1991. *The Moisture Control Handbook – New Low-rise, Residential Construction*, ORNL/Sub/89-SD350/1. Martin Marietta Energy Systems, Oak Ridge National Laboratory, Oak Ridge, TN., USA.

[38] A mixed climate is one that does not fall under the definitions of heating or cooling climate. In Kenya, heating climates generally include high altitude regions while cooling climates are low-altitude regions. However, each local climate should be evaluated specifically whether it is heating, cooling or mixed.

[39] Cooling warm humid climates are defined as climates where one of both of the following conditions occur: (1) a 19.4°C (66.9°F) or higher wet-bulb temperature for 3000 or more hours during the warmest six consecutive months of the year; (2) a 22.8°C (73.0°F) or higher wet-bulb temperature for 1500 or more hours during the warmest six consecutive months of the year (ASHRAE, 1997, pp. 23.9).

[40] Heating climates are defined as climates with 2200 heating degree days (base 18.3°C (65.0°F) or more (ASHRAE, 1997, pp. 23.5)

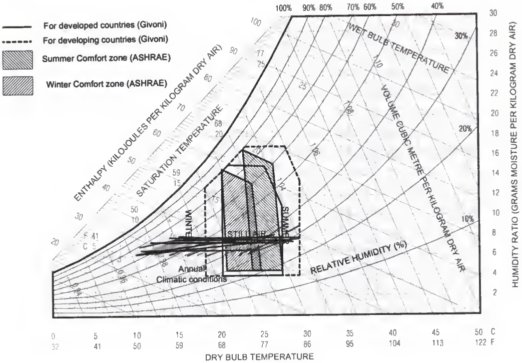

Figure 73: Annual average climate for Nairobi, Kenya, on psychrometric chart

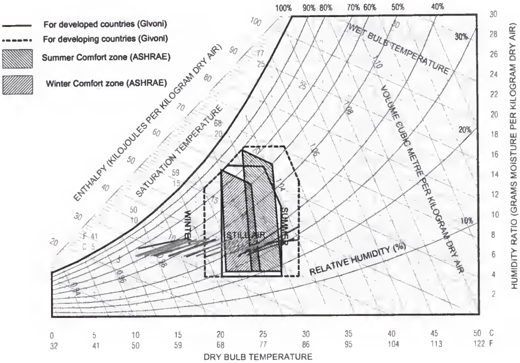

Figure 74: Daily average temperature in January and July in Nairobi, Kenya

Effect of Climate on Thermal Mass

Annually, cooling takes 6% of the period, heating 60% of the period and it is within the comfort zone 34% of the period. Figure 75 shows the ratio of comfort hours, and reveals that cooling is needed between 1:00-5:00pm and heating between 8:00pm-10:00am daily based on outside air conditions. Between 12 noon and 6pm there are some months that are comfortable and others require cooling (January, February). Solar control should be used to prevent overheating.

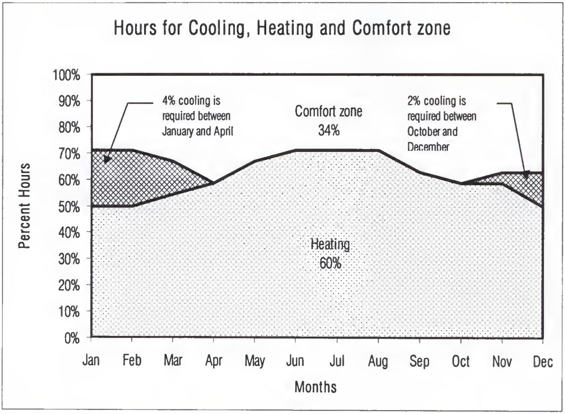

Figure 75: Hours for cooling, heating and comfort zone for Nairobi, Kenya
Based on data from Kenya Meteorological Department[41]

The preceding discussion is based on outdoor conditions that may not necessarily be the same indoors. In fact, indoor temperatures will be affected by internal heat gains from people, appliances and equipment. The timetable of climatic needs by Olgyay (1963, pp. 26-31) was based on *outside temperature*. While it gives an initial indication of the design strategies, Givoni has recognized this as a serious problem and offered a solution through a building bio-climatic chart.[42] It corrects the problem by basing comfort analysis on measured or calculated indoor temperatures.

Givoni[43,44] also showed that well-insulated high thermal mass could lower indoor maximum temperatures by about 2-3°C (3.6-5.4°F) below the outdoor maximum temperatures (Givoni, 1998, pp. 187). Thermal mass can change indoor conditions. The larger the diurnal swings in outdoor temperature, the more important the effect of thermal mass, especially in buildings of continuous occupancy like residences.

Humphreys[45] in summarizing 36 previous studies on comfort in different countries derived a formula correlating comfort temperatures (T_{co}) with mean monthly outdoor air or globe temperature (T_m) of the location:

$T_{co} = 2.56 + 0.831\ T_m\ (^\circ C)$

Humphreys[46] also compared "free-running" buildings (passive and naturally ventilated) with mechanically controlled buildings. He observed that:

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[41] Kenya Meteorological Department. 1984. Climatological Statistics for Kenya. Dagoretti Corner, Ngong Road, Nairobi, Kenya, Ministry of Transport and Communications pp. 60.

[42] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. Van Nostrand Reinhold, New York pp. 27.

[43] Ibid. pp. 187

[44] Givoni, Baruch. 1992. Comfort, climate analysis and building design guidelines, *Energy and Buildings*, Vol. 18 No. 1 pp. 11-23. Amsterdam: Elsevier Science Limited.

[45] Humphreys, Reverend Michael A. 1975. Field Studies of thermal comfort compared and applied. *Building Research Establishment*, Current Paper. CP 76/75, Garston, Watford, UK.

$T_{co} = 11.9 + 0.534\ T_m$ (°C) (passive solar building ranging $10 \leq T_m \leq 34$°C)

$T_{co} = 0.0065T_m^2 + 0.32\ T_h + 12.4$ (°C) (mechanical-systems building ranging $-24 \leq T_m \leq 23$°C and $18 \leq T_h \leq 30$°C) where T_h is the average daily maximum temperature of the hottest months of the year.

Nicol and Roaf[47] proposed an adaptive algorithm suitable for determining comfort temperatures (T_{co}) in Pakistan. It uses simple outdoor temperature calculated from the preceding month ($T_{m'}$):

$T_{co} = 17.0 + 0.38\ T_m$ (°C) (passive solar building)

A similar relationship of comfort temperature on mean outdoor temperature by Auliciems and de Dear[48] is:

$T_{co} = 17.6 + 0.31\ T_m$ (°C) (passive solar building)

There are limitations to using these equations for Nairobi, Kenya, because of the differences of latitude, altitude, geography, climate and the need to establish a localized thermal comfort standard. Using the outdoor temperature in Nairobi and the above stated three equations, the following speculative comfort temperatures were established:

Table 12: Comfort temperatures (°C) for Nairobi, Kenya

Month	*Measured*	*Humphreys*	*Nicol and Roaf*	*Auliciems and de Dear*
February	21.7	23.5	25.2	24.3

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[46] Humphreys, Reverend Michael A. 1978. Outdoor temperatures and comfort indoors. *Building Research and Practice*, 62, pp. 92-105.

[47] Nicol, J. Fergus and Susan Roaf. 1996. Pioneering new indoor temperature standards: the Pakistan project. *Energy and Buildings*, 23 (1996) 169-174. Amsterdam: Elsevier Science Limited.

[48] Auliciems, A.and Richard de Dear. 1978. Air conditioning in Australia, I. Human thermal factors, *Architectural Science Review*, 29 (1978) 67-75.

The above algorithms were made in studies done under "free-running", or natural or passive solar conditions in various climates. There is therefore a limitation to which they can be used, however, they provide an indication in other climates. In cooling and heating load calculations, a reduced difference between indoor and outdoor temperatures (ΔT) implies a reduction in energy use ($Q = UA \times \Delta T$).[49] Although the Pakistani climate is different, the studies by Nicol and Roaf,[50] and Nicol *et al.* [51] provide the basis of the Figure 76. The outdoor maximum, minimum and mean temperatures are plotted with the indoor comfort temperatures. The mean comfort temperature is 23.7°C and this may be achieved passively using thermal mass.

Applying the Results to Passive Solar Buildings

In Figure 76, the comfort temperature (23.7°C) is very close to the outdoor maximum temperature. As a result, nighttime ventilation is likely to be effective in lowering indoor temperatures that rise due to internal heat gains in the day. Passive solar heating is useful in the morning hours when temperatures are still low. As in the Pakistan study, since comfort temperatures are above the mean outdoor minimum temperatures, the use of thermal mass with nighttime ventilation should enable comfort to be achieved without mechanical cooling (Nicol and Roaf, 1996, pp. 173). This is a general observation because most buildings in this region already employ such passive methods in vernacular buildings.

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[49] $Q=UA \times \Delta T$ is standard heat loss/gain calculation where Q is the rate of heat flow (Btu/h or W), U is the thermal transmittance (Btu/h ft^2 F or W/m^2 C) of the material through which is flowing and A (ft^2 or m^2) the surface area of the face the heat is flowing. ΔT is the difference in temperature (°F or °C) between the two sides of the material.

[50] Nicol, J. Fergus and Susan Roaf. 1996. Pioneering new indoor temperature standards: the Pakistan project. *Energy and Buildings*, 23 (1996) 169-174. Amsterdam: Elsevier Science Limited.

[51] Nicol, J. Fergus, Iftikhar A. Raja, Arif Allaudin, Gul Najam Jamy. 1999. Climatic variations in comfortable temperatures: the Pakistan projects. *Energy and Buildings*, 30 (1999) 261-279. Amsterdam: Elsevier Science Limited.

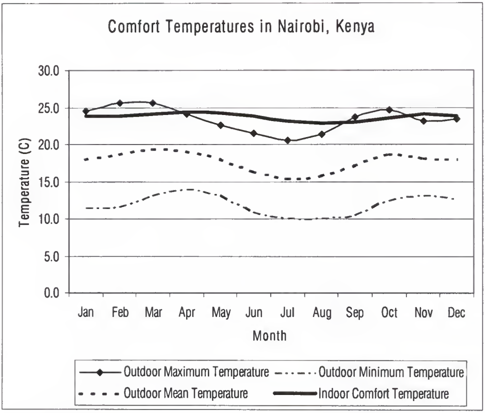

Figure 76: Comfort temperatures in Nairobi, Kenya

Buildings in Kenya

While this section does not describe in detail the thermal properties of the examples of buildings shown herein, they offer a quick view of some of the traditional and contemporary architecture. In both cases, buildings tend to be built with massive high capacity materials to provide thermal inertia for temperature swings.

Traditional African Architecture

Adobe walls and grass-thatched roofs are the basic building materials for the traditional African round house. The building has few windows and the overhangs are usually deep. The roofs need fast water shedding for quick runoffs because when the rains come they usually pour in heavy torrents.

In traditional African societies, the basic work takes place outdoors. Hence, control of the luminous environment indoors is less critical than protection against thermal extremes. An overview of these issues was discussed in a study[52] in 1998. It is a commentary on science and architectural design issues between vernacular and contemporary architecture in East Africa.

The traditional house is built in natural settings. A recent study by Baker[53] asserts: "we have a deep hereditary affinity for the natural world and that modern life in the built environment increasingly isolates us from it". Houseplant buying habits are most common in urbanized areas. A study[54] in Norway compared two large groups of office workers in about 60 individually occupied offices. Complaints of neuro-psychological symptoms, such as fatigue, headache and concentration problems, were reduced by 23% in the case of rooms with plants. Figure 77 shows the floor plan of a round house. It is thermally massive walls shaded all round by deep roof overhangs.

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[52] Ogoli, David Mwale. 1998. Towards green-sensibility in African architecture: A climate-sensitive approach to design in East Africa, in *The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates Proceedings* by Jerry Matthews, Jeff Haberl and Dawna Rosenkranz (eds), pp. 419-427. Fort Worth, Texas: Texas Building Energy Institute.

[53] Baker, N. V. 2000. We are all outdoor animals in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 553-555. James & James (Science Publishers) Ltd.

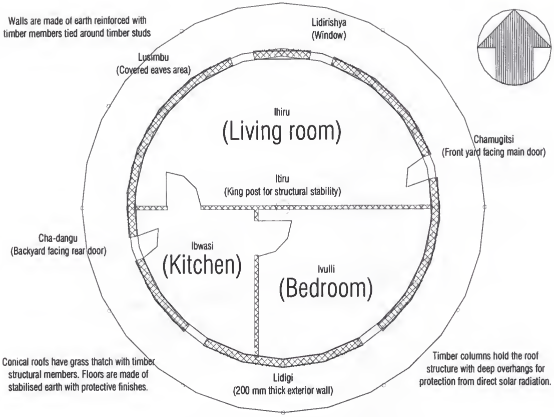
Walls are made of earth reinforced with timber members tied around timber studs
Lidirishya (Window)
Lusimbu (Covered eaves area)
Ihiru
(Living room)
Chamugitsi (Front yard facing main door)
Itiru (King post for structural stability)
Cha-dangu (Backyard facing rear door)
Ibwasi
(Kitchen)
Ivulli
(Bedroom)
Conical roofs have grass thatch with timber structural members. Floors are made of stabilised earth with protective finishes.
Lidigi (200 mm thick exterior wall)
Timber columns hold the roof structure with deep overhangs for protection from direct solar radiation.

Figure 77: Plan of an African traditional round house

Walls are dark-colored massive adobe and roofs have high insulation. Around the country, heavy mass is used in old and new buildings alike. The need to control and moderate temperature swings is achieved through various means (thermal mass, etc.).

Contemporary Architecture

The evolving plan shown in the previous discussion has grown from pure circular geometry to crisp pure rectilinear forms. Figure 78 shows an example of a passive solar house plan developed in Nairobi. It utilizes high thermal mass especially in the roof, floors and on east-west walls. Most openings are on the north-south walls.

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[54] Fjeld, T. et al. 1998. The effect of indoor foliage plants on the health and discomfort symptoms among office workers. *Indoor Built Environment* 7, 1998. Cited by Baker, 2000, pp. 555.

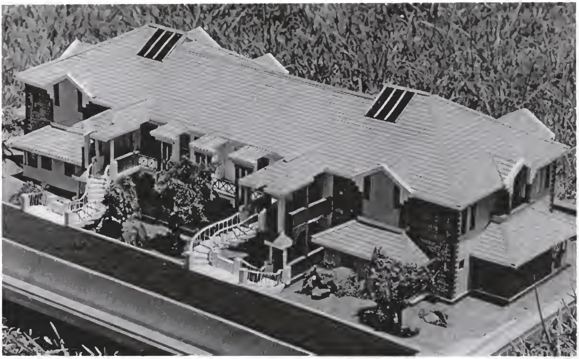

Figure 78: Residential units with solar access elements
Source: Architect Samuel Kigondu[55]

Conclusion

The climate of Nairobi, Kenya, is moderate. There are 392 cooling degree-days and 215 heating degree-days base 18.3°C (65°F). Expressing outdoor temperature more specifically in annual hours, cooling period is 6%, moderate heating is 60% and conditions within the comfort zone is 34%. Average diurnal temperature variation is about 13.5°C (25°F). Climatological statistics show that temperature drops a rate of about 5.9°C for every 1000-metre rise (about 3.24°F for every 1000-foot rise). Altitude and temperature relate as follows:

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[55] Samuel Kigondu is a Principal Architect with Messrs ***A-One***, Architects and Interior Design Consultants, A-One Studio, Ralph Bunche Road, off Valley Road, P. O. Box 64348, Nairobi, Kenya. Their international telephone numbers are: (254) 272-0456, (254) 272-1295, (254) 272-6483, (254) 272-8922.

$$\text{Mean Temperature } (^\circ\text{C}) = 28.7 - 0.00590A_{\text{metres}}$$

$$\text{Mean Temperature } (^\circ\text{F}) = 83.7 - 0.00324A_{\text{feet}}$$

Where A is the altitude above sea level in metres or feet (as indicated). As altitude increases there is a point at which temperature crosses into, and out of, the comfort zone.

Traditional and contemporary buildings in Kenya have consistently used high thermal mass in the roofs, walls and floors. It appears that local people naturally resorted to this form of construction as a result of their inherent advantages. It seems that thermal mass is a good solution to this climate.

Psychrometric charts show that early morning low temperatures can be controlled by (1) thermal mass with sufficient time lag and (2) early direct solar heat gains. Considering that sunrise at the equator is at 6:15am (± 30mins depending on the time of the year), thermal mass should have a time lag of over 12 hours. Some observations show that the traditional round African house is most comfortable when it has high mass.[56,57]

Anecdotal evidence suggests that where everyday people wear lightly, the buildings tend to be light mass (timber, thatch, etc.), and where everyday people dress heavily, the buildings tend to be high mass (stone, concrete, etc.).

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[56] Sharples, Steve and Albert Malama. 1996. Thermal performance of traditional housing in the cool season of Zambia. *Renewable Energy*, Vol. 8, Issues 1-5, pp. 190 – 193, May 1996. Amsterdam: Elsevier Science Limited.

[57] Malama, Albert and Steve Sharples. 1997. Thermal performance of traditional and contemporary housing in the cool season of Zambia. *Building and Environment*, Vol. 32, No. 1, pp. 69 – 78, 1997. Amsterdam: Elsevier Science Limited.

CHAPTER 4
THERMAL COMFORT AND THERMAL MASS

Introduction

Thermal comfort requirements have been a topic of much formal laboratory and field research. Brager and de Dear[1] asked a very important question: What constitutes a "comfortable" thermal environment? The answer to this deceptively simple question has profound implications for the way buildings are designed and operated relative to the amount of energy required to maintain long-term human survival. It is important to understand the thermal interchanges between humans and their environment if the full potential effects of thermal mass are to be experienced. This chapter is devoted to explain this phenomenon through a survey of current literature on thermal comfort research.

Kenya is a country with limited energy resources yet there is a developing trend to adopt high-energy air conditioning in new building projects largely because designers do not examine all environmental design opportunities and constraints. The difference between design indoor temperature and outdoor temperature is basic in HVAC load and sizing calculations. International indoor temperature standards (ASHRAE *Standard 55-1992*[2] and ISO *Standard 7730*[3]) are used in current sizing recommendations for HVAC systems in Kenya. However, these standards do not take into account climatic variation and often have a very narrow temperature band that can only be met by air-conditioning. Different criteria, indices and standards have been developed to assist architects and engineers to design buildings that are comfortable. Human physiological factors like the fundamental thermodynamic processes in heat exchange between the body and the environment were not be dealt with since they were beyond the scope of this dissertation.

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[1] Brager, Gail S. and Richard J. de Dear. 1998. Thermal adaptation in the built environment: a literature review. *Energy and Buildings* 27 (1998) 83-96. London: Elsevier Science Ltd.

[2] ASHRAE. 1992. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard 55-1992.* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[3] International Standard Organization (ISO). 1994. Moderate thermal environment- Determination of the PMV and PPD indices and Specification of the conditions for Thermal Comfort. *ISO Standard 7730.* Geneva Switzerland.

This chapter dwells on physical environmental indices: dry-bulb temperature, mean radiant temperature, humidity, and air movement. It takes into cognizance the fact that occupants of different building types in different climates in different parts of the world seem to define comfort in different terms.

Recent Studies in Thermal Comfort in Buildings

Climate Chamber and Field studies

The "comfort zone" is an appropriate design goal for a deterministic mechanical system but analysis of many international field studies by researchers has questioned its relevance to passive solar buildings (Humphreys, 1975, 1976; Auliciems, 1986;[4] Forwood, 1995, pp. 122-131;[5] Baker and Standeven, 1996, pp. 175-186;[6] Standeven and Baker, 1995, pp. 161-168;[7] Milne, 1995, pp. 182-189[8]). Givoni revised his already authoritative and notable work on the building bio-climatic chart having recognized this new position.[9] These revisions reflect a paradigm shift in thermal comfort for people relative to their thermal environment.

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[4] Auliciems, A.and Richard de Dear. 1978. Air conditioning in Australia, I. Human thermal factors, *Architectural Science Review*, 29 (1978) 67-75.

[5] Forwood, G. 1995. What is thermal comfort in a naturally ventilated building? in: Nicol, Humphreys, Sykes, Roaf (eds.) *Thermal Comfort*. London: E and F. N. Spoon 1995, pp. 122-131.

[6] Baker, Nick and Mark Standeven. 1996. Thermal Comfort in Free-Running Buildings. *Energy and Buildings*, 23 (1996) 175-182. Amsterdam: Elsevier Science Ltd.

[7] Standeven, M. A. and Nick V. Baker. 1995. Comfort conditions in PASCOOL surveys. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century*. Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 161-168.

There is mounting evidence[10,11,12,13,14] that confirms that thermal perceptions are affected by factors that are not recognized by current comfort standards. The factors include thermal history, non-thermal stimuli and psychological expectations. These perceptions are most noticeable in naturally ventilated buildings where expectations are distinctly different from air-conditioned buildings. McIntyre (1980a) stated that "a person's reaction to a temperature which is less than perfect will depend very much on his expectations, personality and what else he is doing at the time".[15] Brager and de Dear (1998, pp. 87) added: "anecdotal evidence suggests that building occupants become accustomed to levels of warmth prevailing within buildings on time scales of weeks to months". They concluded that there is a distinction between thermal comfort responses in

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[8] Milne, G. R. 1995. The energy implications of a climate-based indoor air temperature standard. *Standards for Thermal Comfort: Indoor air temperatures for the 21st century*. Edited by F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London: E & FN Spon pp. 182-189.

[9] Givoni, Baruch. 1998b. *Climate Considerations In Building And Urban Design*. Van Nostrand Reinhold, New York pp. 45.

[10] Humphreys, Reverend Michael A. 1976. Field Studies of thermal comfort compared and applied. *Building Services Engineer*, 44, pp. 5-27.

[11] Humphreys, Reverend Michael A. 1996. Thermal comfort temperatures world-wide – The current position. *Renewable Energy*, Vol. 8 Issues 1-5 May 1996, pp139-144. Amsterdam: Elsevier Science Ltd.

[12] Baker, Nick and Mark Standeven. 1996. Thermal Comfort in Free-Running Buildings. *Energy and Buildings*, 23 (1996) 175-182. London: Elsevier Science Ltd.

[13] Brager, Gail S. and Richard J. de Dear. 1998. Thermal adaptation in the built environment: a literature review. *Energy and Buildings* 27 (1998) 83-96. Amsterdam: Elsevier Science Ltd.

[14] Karyono, Tri Harso. 2000. Report on thermal comfort and building energy studies in Jakarta. *Building and Environment* 35 (2000) 77-90. Amsterdam: Elsevier Science Limited.

[15] McIntyre, D. A. 1980a. Design requirements for a comfortable environment, in: K. Cena, J. A. Clark (eds). Bio-engineering, Thermal Physiology and Comfort. Amsterdam: Elsevier, pp. 157-168.

air-conditioned vs. naturally ventilated buildings.[16] It leads to another emerging observation of psychological adaptation resulting from one's thermal experiences and expectations (Baker and Standeven, 1996, pp. 180). Psychologically, a person's perception of, or response to, the thermal experience appears altered. Paciuk[17] and Williams[18] found that perceived degree of control is one of the strongest predictors of thermal comfort. People who have greater control over their indoor environment are more tolerant of wider ranges in temperature (Leaman and Bordass, 1999, pp. 4; Bunn, 1993, pp. 25-27). These "adaptive errors" are the cause of discrepancy between observed comfort temperatures from field studies and predicted comfort temperatures from climate chamber experiments (Baker and Standeven, 1996, pp. 175).

Evidence from Environmental Psychological

Several studies[19,20] describe some aspects of thermal comfort research to which environmental psychology makes a contribution. They suggest that a psychological dependent variable such as thermal comfort should be decided on the basis of physical and non-physical independent variables. They appear to support the view that thermal comfort is wider than most technical "standards" demand; thermal comfort should include, alongside the measurement of physical variables (temperature, humidity, and wind), "an important classificatory variables (gender, age, education, etc.), socio-cultural (employment status, place of residence, background), psychological (knowledge, experience, self-perceived cold-naturedness, the psychological effect of visual warmth by a fireplace, for example) and contextual variables" (Heijs and Stringer, 1988, pp. 245).

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[16] Brager, Gail S. and Richard J. de Dear. 1998. Thermal adaptation in the built environment: a literature review. *Energy and Buildings* 27 (1998) 83-96. London: Elsevier Science Ltd.

[17] Paciuk, M. The role of personal control of the environment in thermal comfort and satisfaction at the workplace, Coming of age, EDRA 21/1990, in: R. I. Selby, K. H. Anthony, J. Choi, B. Orland (eds.). *Environmental Design Research Association*, Oklahoma City, OK, 1990, pp. 303-312.

[18] Williams, R. N. 1995. Field investigation of thermal comfort, environmental satisfaction and perceived controls levels in UK office buildings. *Healthy Buildings*.

[19] Heijs, Wim and Peter Stringer. 1988. Research on residential thermal comfort: some contributions from environmental psychology. *Journal of Environmental Psychology* (1988) 8, 235-247. New York: Academic Press Limited.

Rohles (1980, pp. 541-551) reported a number of experiments in which he investigated the psychological variables of thermal comfort. The idea was to establish phenomenon that made subjects in an experiment to respond the way they did. Most climate-chambers looked like cold stores and he felt this psychologically influenced perceptions. When the room was clad with wood and given a carpet floor and made homely with appropriate furniture, responses were more positive.

Rohles performed subsequent experiments where they placed in the room a large thermometer that showed constant temperature even though in reality the temperature was gradually lowered. The subjects recorded a cooling effect but they judged that the environment was in thermal comfort.

A third experiment was repeated with heating and the results were similar. Seemingly unrelated factors such as light, furnishing and knowledge of the temperature, culture and experience have a role in thermal comfort. Rohles (1980, pp. 541-551) concluded: "To deny or ignore the psychology involved in comfort measurement is not only shortsighted, but treats the human subject as a machine, which it is not". Rohles[21]

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[20] Rohles, F. H. 1980. Temperature or temperament: a psychologist looks at thermal comfort. *ASHRAE Transactions*, 86, 541-551. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[21] Rohles, F. H. 1981. Thermal comfort and strategies for energy conservation. *Journal of Social Issues*, 37, 132-149.

also indicated that alongside control of physical variables (air temperature, mean radiant temperature, humidity and air movement), adjustments in the amount of furnishing and in space and lighting could probably provide a solution to improving thermal comfort.

In their book, *Environmental Psychology*, Heimstra and Mcfarling[22] described the emerging importance and understanding of "the relationships between human behavior and the physical environment". Psychologists and behavioral scientists agree that the environment (thermal, visual, acoustic, olfactory, etc.) shapes human behavior.

Many major US corporations have cited daylighting systems as significantly increasing worker productivity and reducing absenteeism.[23,24] These studies showed that students in daylit schools outperform their counterparts in "conventional" schools when assessed by a team of teachers and psychologists for a year in their regular learning conditions (UC Berkeley *Wellness Letter* 1996; and *Psychology Today*, 1994). The results were seen to hold true when students were flip-flopped between the two environments during one half of the testing period.

In a study on "Health and behavior of children in classrooms with and without windows", Kuller and Lindsten[25] assessed the effects of light on the production of stress hormones, classroom performance, body growth, and sick leave, of 90 school children in their school environment for a duration of one year. The children were placed in four classrooms differing in respect to the access of natural daylight and artificial light. They concluded that windowless classrooms should be avoided for permanent use because natural daylight contributes to better health and behavior of students.

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[22] Heimistra, Norman W. and Leslie H. McFarling. 1974. *Environmental Psychology*. Monterey, CA: Brooks/Cole Publishing Company, pp. 5.

[23] University of California, Berkeley, *Wellness Letter* February 1996 v12 n5 pp. 8 (1)

[24] *Psychology Today* March-April 1994 v27 n2 pp. 8 (2)

[25] Kuller, Rikard and Carin Lindsten. 1992. Health and behavior of children in classrooms with and without windows. *Journal of Environmental Psychology* (1992) 12, 305-317. New York: Academic Press Limited.

In 1984, Ulrich[26] illustrated that natural daylight had an influence on surgical patients in the recovery room. Ulrich found that surgical patients assigned to rooms with natural light had shorter post-operative hospital stays, received fewer negative evaluative comments in nurses' notes, and took fewer potent analgesics than matched patients in similar rooms in windowless units or units with windows facing a brick building façade. Wilson[27] did a clinical research in 1972 by comparing surgical patients in an intensive care unit without windows and with patients in an intensive care unit with windows. He observed development of organic matter between the two cases and concluded that the presence of windows was highly desirable for the prevention of sensory deprivation. These examples show the long understood view that light has profound psychological and physiological impact on humans (Kuller, 1981).[28]

Research Methods in Thermal Comfort Studies

As previously stated, there are two methods currently used in thermal comfort studies: experiments in climate-chambers and field studies. The climate chamber is based on a heat-balance model whereby subjects in a carefully controlled environment are subjected to different levels of physical environmental parameters and their "neutral" heat balance point established. Pioneer thermal comfort work (ASHRAE, ISO, and

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[26] Ulrich, R. S. 1984. View through a window may influence recovery from surgery. *Science*, 224, 420-421.

[27] Wilson, L. M. 1972. Intensive care delirium. The effect of outside deprivation in a windowless unit. *Archives of Internal Medicine*, 130, 225-226.

[28] Kuller, R. 1981. Non-visual effects of light and color. Annotated bibliography. Document No. 15. Stockholm: Swedish Council for Building Research.

Fanger[29,30]) was done based on this model. On the other hand, field studies (adaptive model) are best in assessing adaptations to the "real world". Humphreys (1975, 1976) and Nicol *et al.* (1996, 1999) have led research in field studies.

Climate-chamber studies done at the Institute for Environmental Research at Kansas State University by Rohles and Nevins (1971)[31] and Rohles (1973)[32] showed that there are correlations between comfort level, temperature, humidity, sex, and length of exposure. These correlations were discussed fully by ASHRAE (1981, pp. 8.18-8.26 and 1997, pp. 8.12). Subjects in the comfort studies were asked to judge the conditions (preferred temperature) in a space and record it using the ASHRAE thermal sensation numerical scale (Table 13):

Table 13: ASHRAE Thermal sensation scale

Scale	*Thermal sensation*
+3	Hot
+2	Warm
+1	Slightly warm
0	Comfortable, neutral
-1	Slightly cool
-2	Cool
-3	Cold

Source: ASHRAE, 1997, pp. 8.12

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[29] Fanger, P. O. 1967. Calculation of thermal comfort: introduction of a basic comfort equation. *ASHRAE Transactions* 73 (2): III.4.1.

[30] Fanger, P. O. 1970. Thermal Comfort: Analysis and Applications in Environmental Engineering. New York: McGraw-Hill Book Company.

[31] Rohles, F. H. and R. G. Nevins. 1971. The nature of thermal comfort for sedentary man. *ASHRAE Transactions*, 77 (1) p239-246, 1971. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[32] Rohles, F. H. 1973. The revised modal comfort envelope. *ASHRAE Transactions* 79 (2):52. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

Thermal Comfort and Thermal Mass

Thermal comfort is not an exact concept and human responses with regard to comfort do not occur as a response to an exact temperature (Santamouris and Asimakopolous, 1996, pp. 151). Application of any given comfort standards based on a set of comfort indices can lead to more energy usage for air-conditioning in buildings even in cases where it is physiologically not really needed (Givoni, 1998b, pp.35). The extensive literature on thermal comfort has been made in two broad categories due to the methodology, namely, climate chamber experiments and field studies. Both approaches are useful in giving a true realistic picture of the dynamics of thermal comfort and energy in buildings. The optimum energy usage in buildings requires the use of a hybrid of passive and active systems. Thermal mass has the thermal inertia to absorb and store heat during daytime hours and return it to the space later. The following is a summary of major studies that have shaped current theories.

Studies by Olgyay

Victor Olgyay, while at the School of Architecture and Urban Planning at Princeton University in 1963, wrote a masterful book, *Design with Climate*, that provided in-depth study regarding the connection between architecture and several sciences. He referred to biology for definition of the measure and purpose of human comfort requirements. He used meteorology for precise description of existing climatic conditions. Finally, he tied these to engineering sciences for rational solutions and execution. He was the first to develop a bio-climatic diagram (Figure 10, Chapter 1). The chart has relative humidity on the horizontal axis and temperature on the vertical axis. The lower temperature limits of the comfort zone are 21°C (70°F) while the upper limits are 27.8°C (82°F). The upper temperature limit is humidity-dependent. Wind through a space is a good strategy in extending the comfort zone at higher temperature and higher humidity.

However, this chart has some problems when used in hot dry climates where over-heating is a common problem. In high-mass buildings indoor night temperatures, even in unheated buildings, may be about 5°C (9°F) or more above the outdoor temperature (Givoni, 1998, pp. 28). The chart also uses outdoor temperatures to assess the indoor temperatures. This means that using the Olgyay charts to define the times for heating or cooling can lead to overestimation of heating or cooling loads.

Studies by Givoni

Givoni defines thermal comfort as "the range of climatic conditions considered comfortable and acceptable inside buildings. It implies an absence of any sensation of thermal (heat or cold) discomfort" (Givoni, 1998, pp. 3). In 1976 he developed the building bio-climatic chart to address the problems associated with the charts by Olgyay. It is based on indoor temperatures and suggests boundaries of the climatic conditions on the psychrometric chart within which various building design strategies (including passive and low energy cooling systems) can provide indoor comfort in hot climates without air-conditioning. The boundaries of acceptable conditions for still air are shown on the psychrometric chart in the figure below. Givoni suggested temperature ranges of acceptable conditions in still air, for people living in developed countries as 18 to 25°C (64.4 to 77°F) in winter and 20 to 27°C (68 to 80.6°F). For people living in hot developing countries, Givoni suggested elevations of 2°C (3.6°F) in the upper temperature limit (Givoni, 1992, pp. 16; 1998, pp. 38-39).

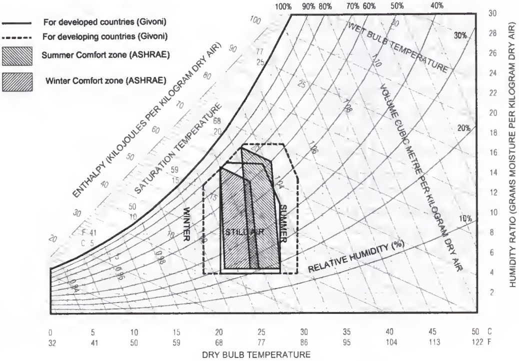

Figure 79: Boundaries of acceptable conditions for still air
Source: Givoni, 1998b, pp. 38

Givoni (1998, pp. 5) stated that different comfort standards are justified for countries with different climatic conditions and stages of economic development. "It is impossible to have 'universal' comfort indices and standards" (Givoni, 1998, pp. 36). Thermal comfort standards that use few energy resources, and respect the cultures and climates of the world, are most likely to come from strategic field-study research projects, interpreted according to the adaptive concept (Humphreys, 1996, pp. 143).

Figures 80-81 show the boundaries of outdoor temperature and humidity within which indoor climate can be provided by natural ventilation during the day with indoor airspeed about 2 m/s (400 fpm) and general design strategies.

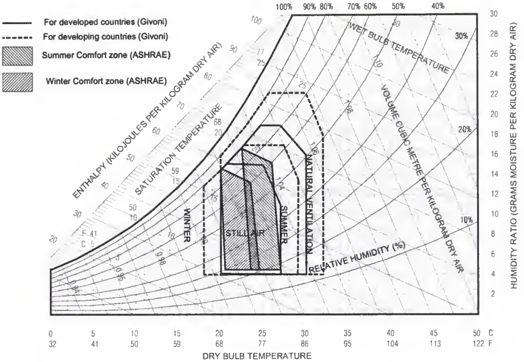

Figure 80: Thermal comfort limits as extended by natural ventilation

Source: Givoni, 1998b, pp. 40

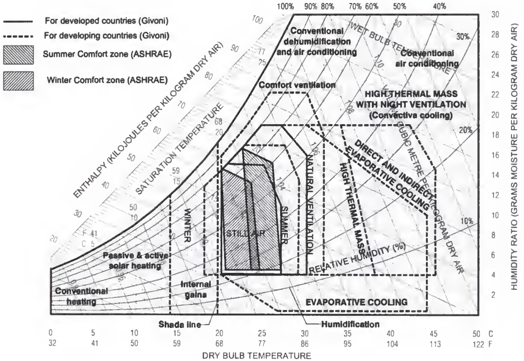

Figure 81: Boundaries and design strategies for thermal comfort

Impact of Thermal Mass on Thermal Comfort

Athienitis and Chen[33] made an experimental investigation on various types of floor thermal mass systems. For thermal comfort, they noted that thermal mass on the floor stores more solar energy than other elements of the building enclosure. Their findings were that for an outdoor test room, solar beam radiation could cause a local floor surface temperature in the illuminated area by 8ºC higher than in the shaded area. Partial carpet cover further increases floor surface temperature differences up to 15ºC when solar radiation is absorbed. Solar radiation stored in the floor thermal mass was found to reduce heating consumption significantly (30% or more).

A study by Geros *et al.* (1999, pp. 141-154) experimentally evaluated night ventilation on thermal mass. It discussed an index to characterize the contribution of night ventilation techniques to the indoor thermal comfort conditions by determining the number of overheating hours. The study concluded that a passive solar building[34] had day peak temperatures reduced by up to 3ºC (5.4ºF) due to the mass. Figure 82 shows annual cooling load and heating energy a Nairobi experimental test house. The relationships are:

$$\text{Cooling energy} = 3.1697\,(\text{ACH})^2 - 0.1461\,(\text{ACH}) - 0.4038$$

$$\text{Heating energy} = 8.4552e^{-0.4081\,(\text{ACH})}$$

ACH is air-changes per hour.

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[33] Athienitis, A. K. and Y. Chen. 2000. The effect of solar radiation on dynamic thermal performance of floor heating systems in *Solar Energy* Vol. 69, No. 3, pp. 229-237, 2000. Amsterdam: Elsevier Science Limited.

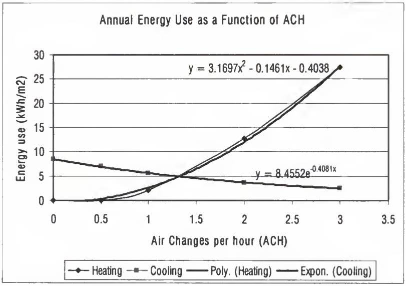

Figure 82: Annual energy use a function of air changes per hour
Computed using *Energy-10*[35]

Conclusions

Thermal comfort requirements have been a topic of much formal laboratory and field research for over one hundred years. Two most widely used international comfort standards are ASHRAE *Standard 55* and ISO *Standard 7730.* They define conditions of comfortable thermal environment for steady-state (HVAC systems) conditions.

The "comfort zone" is an appropriate design goal for a deterministic mechanical system but analysis of many international field studies by researchers has questioned its relevance to passive solar buildings. Of the existing thermal comfort models known, the adaptive model is best suited to assess passive solar buildings. It accounts for physical

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[34] Geros et al. (1991, pp. 141-154) referred to a passive solar building as "free-floating". This is the term used in their study.

[35] Balcomb, J. Douglas. 1996. *Designing low-energy buildings: Passive solar strategies and Energy-10 Software.* Developed in collaboration with Passive Solar Industries Council, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory and US Department of Energy (DOE).

environmental parameters as well as personal and psychological adaptations. Thermal mass has the thermal inertia to moderate and delay daytime temperature.

Night ventilation can extend the effectiveness of thermal mass. It can also have other energy implications. Ventilation in the form of air changes per hour (ACH) can extend the comfort zone. They also have an impact on energy use.

Annual cooling load and heating energy a Nairobi experimental test house has produced the relationships:

$$\text{Cooling energy} = 3.1697\,(\text{ACH})^{2} - 0.1461\,(\text{ACH}) - 0.4038$$

$$\text{Heating energy} = 8.4552e^{-0.4081\,(\text{ACH})}$$

Thermal comfort standards vary from climate to climate and are not uniform everywhere. Comfort standards should be conscious of the local climate, culture, economic capability and acclimatization of the people for them to be useful.

CHAPTER 5
ENERGY-EFFICIENCY AND OTHER RELATED FACTORS

Introduction

This chapter discusses energy-efficiency, environmental sustainability issues and other matters that relate to thermal mass. It discusses some simplified design tools for estimating the energy use, indoor temperatures and effects of natural ventilation in buildings with thermal mass. It also briefly discusses non-thermal issues that have direct impact on comfort in buildings including: indoor air quality, acoustics, and life safety systems and lighting.

Solar energy holds the key to sustainable development for the future. A recent study[1] discussed the necessity, speed and strategies to be taken for a transition from an estimated US $ 8 trillion fossil fuel-based infrastructure to a sustainable worldwide energy approach. The study said:

> The world is on a path that is not sustainable. Ahead is our rapidly expanding energy needs, a fundamental component of development; behind follows the environmental destruction, a consequence of the very energy system that brought it to this point.

Solar energy is often regarded as environmentally friendly but at the same time as not economical. A study[2] published by American Solar Energy Society discussed the economics of solar energy. It showed that renewable energy provides new jobs, has long-term reduction in administrative and health costs associated with renewable energies, and, is sustainable. On this note, many organizations'[3,4,5] overall mission is to provide support to governments to strengthen sustainable human development with aims such as:

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[1] Nicklas, Michael. 1996. 40% renewable energy by 2020: An ISES goal, a global necessity in *Advances in Solar Energy: An Annual Review of Research and Development*, by Karl W. Boer (ed) Vol. 11 1996, pp. 415-460. Boulder, Colorado: American Solar Energy Society, Inc.

[2] Scheer, H. 1994. The economy of solar energy in *Advances in Solar Energy: An Annual Review of Research and Development*, by Karl W. Boer (ed) Vol. 9 1994, pp. 307-338. Boulder, Colorado: American Solar Energy Society, Inc.

1. Elimination of poverty.
2. Creation of jobs.
3. Regeneration of the natural environment.

Thermal mass as a passive strategy is sustainable. A look at renewable energy sources, simplified simulation tools, acoustic and lighting issues provide a chance for the proper integration of thermal mass in buildings to ensure a sustainable world.

Energy Research in Kenya: Overview

Renewable energy in the form solar, wind, geothermal and oceanic currents have been used in Kenya in a long time (Walsh, 1969[6]; DuBois, 1970[7]; Tole, 1996[8], Ogoli, 1997[9]). However, Kenya's economy depends on three major sources, namely, wood fuel,

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[3] UNDP: United Nations Development Programme. *Poverty and Environmental Initiative (PEI),* December 2000 at http://www.undp.org/seed/pei/

[4] World Bank. 2000b. *A Brighter Future? Energy in Africa's Development,* December 2000 at http://www.worldbank.org/html/fpd/energy/subenergy/energyinafrica.htm

[5] International Finance Corporation. *IFC Strategic Directions: Executive Summary*, December, 2000 at http://www.ifc.org/images/strategic_summary.pdf

[6] Walsh, J. 1969. Mineral and thermal waters of Kenya in *XXII International Geological Congress*, 19, pp. 105-110.

[7] DuBois, C. G.B. 1970. Minerals of Kenya. *Geological Survey Kenya Bulletin* 11, pp. 66. Nairobi: Government Printers.

[8] Tole, Mwakio P. 1996. Geothermal energy research in Kenya: A review in *Journal of African Earth Sciences*, Vol. 23, No. 4, pp. 565-575, 1996. New York: Pergamon Press.

[9] Ogoli, David Mwale. 1997. Energy in African architecture – Guidelines for Kenya in *Horizon DAT*, Vol. 1, No. 1, pp. 52-62, 1997. Nairobi, Kenya: ICIPE Science Press.

petroleum and electricity. Recent studies[10,11] reviewed and analyzed policy, environment and issues surrounding emerging liberalized petroleum sector in Kenya. National annual demand for energy is estimated at 9.8 million tons of equivalent (TOE) with an annual growth rate of about 3.7% (Republic of Kenya, 1996). The breakdown of energy consumption by primary source is shown in Figure 83.

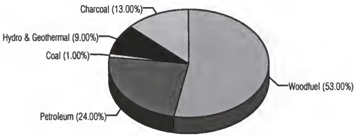

Figure 83: Energy consumption in Kenya by primary source in 1996
Source: Okech and Nyoike, 1999, pp. 46

Geothermal energy for electricity generation is becoming increasingly important in Kenya because of the fact that "(a) Kenya has abundant geothermal resources relative to its electrical power requirements; (b) geothermal electricity is the cheapest form of electrical power in Kenya; and (c) Kenya's potential for generating electricity from hydropower is nearly exhausted" (Tole, 1996, pp. 567). The planned electricity generation from geothermal is only 173 megawatts (MW) (Republic of Kenya, 1997, pp.

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[10] Okech, Benjamin A. and Patrick M. Nyoike. 1999. Energy sector liberalization in Kenya: critical policy issues in petroleum retail market in *Energy Policy*, 27 (1999) 45-46. Amsterdam: Elsevier Science Limited.

[11] Lambert, D. W. H., R. Holland and K. Crawley. 2000. Appropriate battery technology for a new, rechargeable, micro-solar lantern in *Journal of Power Sources* 88 (2000) 108-114. Amsterdam: Elsevier Science Limited.

100). Based on studies[12] of the geothermal fields of Turkana, Bogoria, Eburru, Olkaria, Magadi and Natron, the estimated heat flow in the Kenya rift valley is between 6,882 and 18,680 MW. Although definitive data are lacking, Kenya's geothermal potential is much greater than current total installed electrical power system of 822 MW.

Energy is vital to economic development. Developed countries depend on large amounts of energy to fuel their economy and keep industries running. According to the World Bank:[13] "people in OECD countries spend only 2 to 3% of their income for 'energy', in the developing world, this share is 12% and in the case of the poor is even more". The fact that poor people spend so much of their income on energy emphasizes the importance of energy. Of the 650 million people in Africa, majority has limited access to modern forms of energy. Lack of energy denies millions of people the ability to reduce poverty because they cannot reap the full benefits of their investment of human resources. Human energy is most prevalent in Africa and this hampers real economic development. The World Bank[14] acknowledges that energy is critical to development:

> No country in the world has succeeded in shaking loose from a subsistence economy without access to the services which modern energy provides. The history of development identifies it as one of the prerequisites to facilitate social development and fuel growth. There is no evidence to the contrary. There is, however, voluminous evidence of how lack of access constrains social development and growth. A mark of the importance that people in developing countries attach to energy is that they spend 12% of their income on energy, compared with an average of just 2% in OECD countries. As a 'revealed preference', to use the economic jargon, energy is high on the agenda of those struggling to escape poverty.

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[12] Crane, K. and S. O'Connell. 1983. The distribution and implications of heat flow from the Gregory rift in Kenya in *Tectonophysics*, 94, pp. 253-275.

[13] World Bank. 2000a. *Perspectives on Energy Development.* http://www.worldbank.org/html/fpd/energy/energy_dev.htm

[14] World Bank. 2000b. *A Brighter Future? Energy in Africa's Development,* December 2000 at http://www.worldbank.org/html/fpd/energy/subenergy/energyinafrica.htm

This dissertation is based on the thesis that if buildings use more passive solar energy[15] then more active energy[16] will be available for other sectors of the economy in poverty reduction.

A study[17] funded by USAID was carried out to describe and catalogue renewable energy systems in Kenya. Sources of conventional energy include renewable energies (biomass, wind, hydropower and direct solar), and non-renewable (fossil fuels and geothermal[18] power). Details of some the findings are summarized below. A study by Hankin (1987, pp. 12) and other studies[19,20] show that renewable energies are the most appropriate for rural areas because:

1. Renewable energies make use of local resources;
2. Renewable energies increase rural employment opportunities;
3. Renewable energies help to protect the environment;
4. Renewable energies save foreign exchange;
5. Renewable energies can meet demand scattered over large areas;
6. Renewable energies improve the standard of living.

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[15] Passive solar energy is generally diffuse, low flux and not concentrated. However, domestic applications can be gainfully utilized for photovoltaic electricity, heating, cooling, and other low temperature heat applications. This is renewable energy in the form of direct sun, wind, geothermal and ocean waves.

[16] Active energy is taken to mean concentrated and highly processed forms of non-renewable energy. They includes fossil fuels and nuclear energy.

[17] Hankin, M. 1987. *Renewable Energy in Kenya.* Creative Motives, Nairobi, Kenya.

[18] Geothermal energy is renewable energy but some people categorize it as non-renewable due to the resources and capital required to maintain it.

[19] Flavin, Christopher and Molly O;Meara. 1998. Financing solar home systems in developing countries: Examples of new market strategies in *Advances in Solar Energy: An Annual Review of Research and Development*, by Karl W. Boer (ed) Vol. 12 1998, pp. 123-148. Boulder, Colorado: American Solar Energy Society, Inc.

[20] World Bank. 2000b. *A Brighter Future? Energy in Africa's Development,* December 2000 at http://www.worldbank.org/html/fpd/energy/subenergy/energyinafrica.htm

Wood fuel, hydro and solar energy resources already meet major energy needs in Kenya. More research in renewable energy is needed.

Indoor Air Quality Considerations Regarding Thermal Mass

The behavior of thermal mass is affected by considerations of indoor air quality such as ventilation standards. The Kenya Building Code[21] (1997a, by-law #150 pp. 54) requires that every domestic building be provided with adequate means of ventilation and have a sufficient number of windows suitably positioned for direct communication with external air. This Code emphasizes natural ventilation and natural daylighting noting that mechanical systems have indoor air quality (IAQ) problems.

Ventilation Standards

In Kenya, the Building Code is the ventilation standard. Other standards around the world, however, have been developed to fully embrace the technology of air conditioning. ASHRAE *Standard 62*-89[22] specifies minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to minimize the potential for adverse health effects. Ventilating systems designed and installed according to ASHRAE *Standard 62*[23,24] should not cause conditions that conflict with the thermal comfort ASHRAE *Standard 55*. In the United States of America, this usually means resorting to mechanical systems.

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[21] GK: Government of Kenya. 1997a. *Building Code: Local Government (Adoptive By-Laws) (Building) Order 1968 and The Local Government (Adoptive By-Laws) (Grade II Building) Order 1968*. Nairobi: Government Printer.

[22] ASHRAE. 1989b. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62-1989. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[23] ASHRAE *Standard 62-1999: Ventilation for Acceptable Indoor Air Quality* was released in October 1999. It specifies minimum ventilation rates for nearly 100 different indoor spaces, including hospitals, public assembly buildings and commercial and office buildings. The standard also references maximum acceptable levels of contaminants as set by cognizant organizations.

In United Kingdom, two sources for designing natural ventilation are publications by Chartered Institution of Building Services Engineers (CIBSE, 1997)[25] and the British Standards Institution (BSI, 1991).[26] Even these two, however, have very high standards so much so that to naturally ventilate a traditional African round house would have the equivalent of a mechanical system operating as a wind tunnel to meet the same needs. In Kenya, this fete is normally met adequately by "opening" the building by inexpensive passive systems. Ventilation can affect the effect of thermal mass on indoor climate.

It is widely accepted that reducing ventilation and infiltration for thermal comfort reasons and energy conservation measures can affect indoor air quality. Outdoor air that flows through a building is often used to dilute and remove indoor air contaminants. The size, position and number of windows have profound effect on the ability to use natural ventilation.[27] Natural and/or artificial pressure differences drive natural ventilation, infiltration[28] and exfiltration[29]. Thermal mass, in turn, affects internal building loads.

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[24] ASHRAE. 1999b. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62-1999. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[25] CIBSE: Chartered Institution of Building Services Engineers. 1997. Natural ventilation in non-domestic buildings in *Applications Manual AM10*. London: Chartered Institution of Building Services Engineers.

[26] BSI: British Standards Institution. 1991. *BS 5925: Code of practice for ventilation principles and designing for natural ventilation*. London: British Standards Institution.

[27] Natural ventilation is the intentional flow of air through open windows, doors, grilles, and other planned building envelope penetrations, and it is driven by natural and/or artificially produced pressure differentials (ASHRAE *Fundamentals Handbook* 25.1)

[28] Infiltration is the uncontrolled flow of outdoor air into a building through cracks and other unintentional openings through the normal use of exterior doors for entrance and egress (ASHRAE *Fundamentals Handbook* 25.1).

[29] Exfiltration is the leakage of the indoor air out of a building (ASHRAE *Fundamentals Handbook* 25.1).

Odor and Indoor Air Quality in Occupied Spaces

In the 1980's, research[30,31,32] showed that 80% of *visitors* to an occupied space express odor satisfaction at an outdoor air ventilation rate of 15 cfm (7.5 L/s) per person, while 80% of *occupants* express odor satisfaction at 5 cfm (2.5 L/s) per person. "Since people adapt quickly to many odors, *visitors* judge odor acceptability within 15 seconds after entering the space while *occupants* judge acceptability 15 minutes or more after entering the space" (Stanke, 1999, pp. 41). These studies confirmed the long established people-odor minimum rate[33] and offered a rational explanation for the minimum rate of 5 cfm (2.5 L/s) per person used previously. In many cases, when ventilation is used to pre-cool thermal mass, then also the implications of odors should be taken very seriously.

Some studies[34,35,36] have shown that productivity of 20% of office workers in the USA was raised simply by improved indoor air quality. Rowe (1999) argued that naturally ventilated buildings are the preferred environments because they offer more

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[30] Berg-Munch, B., G. H. Clausen and P. O. Fanger. 1986. Ventilation requirements for the control of body odor in spaces occupied by women. *Environ. Int.* 12:195-200.

[31] Cain, W. S., *et al.* 1983. Ventilation requirements in buildings – I. Control of occupancy odor and tobacco smoke odor. *Atmospheric Environment* 17 (6): 1183-1197. Amsterdam: Elsevier Science Limited.

[32] Fanger, P. O. and B. Berg-Munch. 1983. Ventilation and body odor. *Proceedings of an Engineering Foundation Conference on Management of Atmospheres in Tightly Enclosed Spaces*, pp. 45-50. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[33] Yaglou, C. P., E. C. Riley and D. I. Coggins. 1936. Ventilation requirements. *ASHRAE Transactions* 42: 133-162. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[34] Lorsch, H. and O. Abdou. 1994a. The impact of the building indoor environment on occupant productivity: Part 1: recent studies, measures and costs. *ASHRAE Transactions*, 1994, pp. 741-749. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[35] Lorsch, H. and O. Abdou. 1994b. The impact of the building indoor environment on occupant productivity: Part 2: effects of temperature. *ASHRAE Transactions*, 1994, pp. 895-901. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

[36] Lorsch, H. and O. Abdou. 1994c. The impact of the building indoor environment on occupant productivity: Part 2: effects of indoor air quality. *ASHRAE Transactions*, 1994, pp. 902-912. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA.

personal controls to the occupant. A study[37] on solving the IAQ-energy dilemma argued that energy-efficiency and indoor air quality optimized simultaneously. Ventilation rates and indoor air quality should not adversely affect the effectiveness of thermal mass.

Acoustic Considerations Regarding Building Mass

The use of thermal mass has implications on acoustical environments created in noise-sensitive spaces. Noise may be defined as unwanted, distractive or excessive sound. Airborne noise is noise transmitted through air. There are three basic approaches to reduce the transmission of airborne noise in buildings (Siebein, 1993, pp. 4-1):[38]

1. Reduce the noise of the source.
2. Control or reduce the noise at the listener.
3. Control or reduce the noise along the path of transmission.

The following discussion relates the basics of sound isolation as related to thermal mass and its role in sound attenuation.

Sound Isolation as Related to Thermal Mass

Controlling noise at the source includes using quieter equipment, good acoustical barriers and sound absorbent materials. Controlling the path of the sound implies the need to control airborne noise and flanking transmission, and structure borne noise including impact noise and mechanical system noise (Figure 84). Mass is critical in transmission of low frequency sounds in noise-sensitive spaces like concert halls and theatres.

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[37] Schell, Mike. 2000. Solving the IAQ-energy dilemma: The IAQ dilemma in *Energy Systems* Magazine. P. O. Box 4270, Troy, MI 48099, USA.

[38] Siebein, Gary W. 1993. *Tutorial on Architectural Acoustics*. University of Florida, Gainesville, FL.

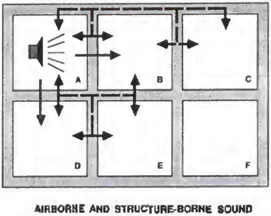

Figure 84: Sound paths through building mass

The Role of Mass in Sound Attenuation

Acoustical materials were studied and discussed in Chapter 2 of *Architectural Acoustics.*[39] It discussed the fact that "all building materials are in a way acoustical because all affect the manner in which sound is reflected, absorbed, or transmitted" (Pirn, 1999, pp. 55). Attenuation is defined by two terms; the difference between the sound levels between two rooms called Noise Reduction (NR) and sound level difference due to the separating barrier called Transmission Loss (TL).

Figure 85 describes this phenomenon. The relationship between transmission loss (TL) and noise reduction (NR) is: $\mathrm{TL} = \mathrm{NR} - 10 \log \frac{a_2}{S}$

Where S is the surface area of the mass barrier and a_2 is the amount of acoustical absorption in the receiving room. Heavy materials have high sound transmission class[40]

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[39] Pirn, Rein. 1999. Acoustical materials and methods in *Architectural Acoustics: Principles and Practice* by Cavanaugh, William J. and Joseph (eds.). New York: John Wiley & Sons, Inc. pp. 55-99.

[40] Sound transmission class (STC) is a single-number rating of the air-borne sound transmission loss TL performance of a construction measured at standard one-third octave band frequencies. The higher the STC rating, the more efficient the construction will be in reducing sound transmission within the frequency

(STC rating). Transmission loss, and therefore noise reduction and sound attenuation in general, depends on frequency. Sound transmission loss increases with building mass.

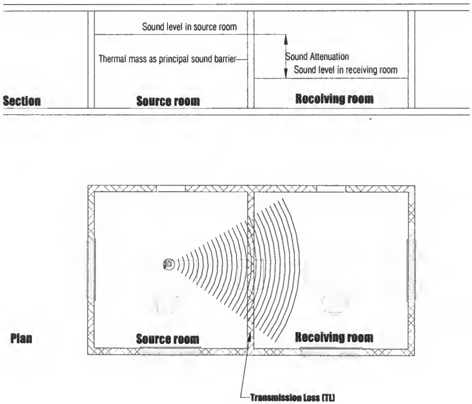

Figure 85: Schematic illustration of airborne sound attenuation in high mass walls

It has been suggested in numerous studies that:

> Theoretically, TL also increases 6 dB with every doubling of the material's mass.[41]
>
> Heavy materials such as concrete such as concrete and masonry perform well in the lower frequencies, are relatively inefficient in the 500 Hz range, and regain their excellence in the higher frequencies.
>
> Lightweight materials such as gypsum board or plaster on studs (also glass) perform poorly in the low frequencies, quite well in the middle frequencies, and again less well at the highest frequencies of interest.[42]

---

range of the test (Egan, 1988, pp. 201). Heavy materials tend to have STC and are particularly useful in enhance low frequency sounds for warmth and brilliance acoustical properties.

[41] Ibid. pp. 57.

High mass materials are useful in attenuating low frequency sounds such as those of mechanical equipment and some musical instruments. Lighter materials are best where speech sound dominates (between the range of 500 to 4000 Hz).

Case studies of recent halls for performing arts and acoustical models studies show a similar trend; heavy massive materials for noise reduction.[43] A detailed study[44] on sound transmission through concrete blocks shows many different ways to improve it. Figure 86 shows transmission loss performance based on equal surface weight for several materials. Heavier materials have higher transmission loss, ass shown by mass law curve.

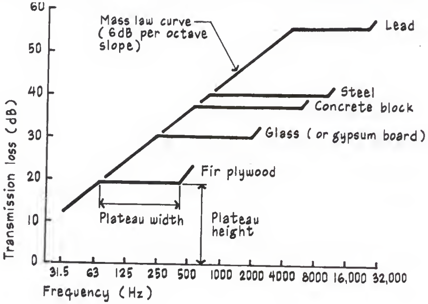

Figure 86: Transmission loss performance based on equal surface weight

Source: Egan, 1988, pp. 181.

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[42] Ibid. pp. 58.

[43] Siebein, Gary W. and Bertram Y. Kinzey, Jr. 1999. Recent Innovations in Acoustical Design and Research in *Architectural Acoustics: Principles and Practice* by Cavanaugh, William J. and Joseph (eds.). New York: John Wiley & Sons, Inc. pp. 233-304.

[44] Warnock, A. C. C. 1992. Sound transmission through two kinds of porous concrete blocks with attached drywall, *Journal of Acoustical Society of America*, 92 (3), pp. 1452-1460.

Higher plateau levels and narrower plateau widths on the figure above indicate better sound-isolating performance on an equivalent weight basis. Heavier masses have relatively good acoustic properties. As Egan (1988, pp. 180)[45] said: "The ideal sound isolating construction would be *heavy, limp*, and *airtight*".

High building mass for noise control improves worker productivity

Leaman and Bordass[46] did a study relating productivity in buildings with five perceived control variables – heating, cooling, lighting, ventilation, and noise. They concluded that noise is the most strongly associated with perceived productivity. Some of the respondents to their survey said that noise has the most disturbing effect on work. Building mass is an important consideration since it affects noise attenuation.

Life Safety Considerations of Thermal Mass

Thermal mass has a dual role in the attainment of thermal comfort and life safety. Floors, walls and roofs affect the spread of fire, and consequently smoke management, and should be chosen to improve life safety. Most high mass materials like concrete can achieve higher fire rating than lightweight materials. One of the most efficient ways known to limit the damage from a fire is to develop compartments (ASHRAE, 1999, pp. 51.1) thereby giving rise to thermal mass within the floors and partitions.

Life safety considerations depend on the type of occupancy of a building; office buildings have different requirements from manufacturing facilities. Buildings need to be protected against fires for life safety. Usually, smoke causes most deaths in fires. The US *Fire Protection Handbook* (NFPA 1997)[47] and *Life Safety Handbook*[48] contain details on fire safety information. According to US National Fire Protection Administration (NFPA) and ASHRAE (1999, pp. 51.1), there are two approaches to fire protection:

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[45] Egan, M. David. 1988. Architectural Acoustics. New York: McGraw-Hill, Inc. pp. 180.

[46] Leaman, Adrian and Bill Bordass. 1999. Productivity in buildings: the "killer" variables. *Building Research & Information* (1999) 27 (1), 4-19. London: E & FN Spon.

1. To protect fire ignition and
2. To manage fire impact.

Building occupants play a major role in protection against fire ignition. Managing fire impact requires a carefully coordinated effort that includes the building design.

Lighting Considerations Regarding Thermal Mass

Heat load in the form of thermal radiation due to lighting requirements has a time lag from the building mass. Figure 87 shows how this absorbed energy contributes to space cooling load only after a time lag, with some part of such energy still present and reradiating after the lights have been switched off.

Since light is a major space load component (ASHRAE, 1997, 28.7), an accurate heat transfer mechanism is needed. Part of light energy is in the form of convective heat but a major portion is in the form of radiation that gets absorbed by thermal mass (walls, floors etc.). This absorbed energy is released slowly depending on the thermal properties of the material. Therefore, lighting systems should be carefully considered.

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[47] NFPA. 1997a. *Fire Protection Handbook*, 18th edition. Quincy, MA: National Fire Protection Administration.

[48] NFPA. 1997b. *Life Safety Code*. ANSI/NFPA *Standard* 101-94. Quincy, MA: National Fire Protection Administration.

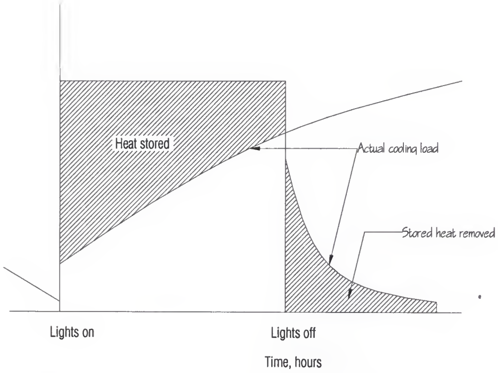

Figure 87: Thermal storage effect in cooling load from lights
Source: ASHRAE 1997, pp. 28.7

Electric lighting and its associated cooling requirement consume 30% to 50% of the energy used in a typical commercial building (Ne'eman *et al.*, 1998, pp. 159-171). McHugh *et al.* (1998, pp. 31-35) investigated a zero energy building, designed to be eventually self-sufficient in energy, i.e. to take zero energy from the electric and natural gas grids. The energy impact of daylighting was observed because it reduced the cooling load. While the productivity benefits from daylighting and cooling are hard to quantify, there is growing evidence that monetary value is high. Having thermal mass for thermal reasons also offers a chance to daylighting strategies that will energy use in buildings.

Conclusions

People in developing countries spend over 12% of their income for “energy”; the OECD countries spend only 2 to 3 % developing world. In the case of the poorest poor, they spend even more than 12%. The fact that poor people spend so much of their income on energy emphasizes the importance of energy in human society.

Thermal mass, the size, position and number of windows have profound effect on the ability to use natural ventilation in passive solar buildings. Studies show that indoor air quality raises the productivity of office workers in buildings.

Heavy materials such as concrete and masonry perform (1) well in the lower frequencies, (2) are relatively inefficient in the 500 Hz range, and (3) regain their excellence in the higher frequencies. High mass materials are extremely useful in attenuating low frequency sounds such as those of mechanical equipment and some musical instruments. Lighter materials are best useful where speech sound dominates (between the range of 500 to 4000 Hz). The ideal sound isolating construction is heavy building mass.

Floors, walls and roofs affect the spread of fire, and consequently smoke management, and should be chosen to improve life safety. Most high mass materials like concrete can achieve higher fire rating than lightweight materials. Building mass has multiple roles in attainment of acoustic noise control, life safety, lighting efficiency and thermal comfort.

CHAPTER 6
ENERGY SIMULATION STUDIES INVOLVING THERMAL MASS

Introduction

Thermal Modeling Methods

Thermal modeling techniques have been developed to accurately represent the thermal performance of buildings by a thermal network method or the transfer function method.[1] Theoretic network considers the building as a network of interconnected elements each assigned an electrical analogue. Heat conduction through thermal mass elements such floors, walls and roofs have resistances and capacitances. Windows are resistances because they do not have thermal mass. Examples of these are shown in Figures 88 and 89.

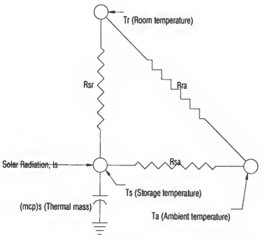

Figure 88: Thermal circuit showing thermal mass in a passive solar building
Source: Goswami *et al.*, 2000, pp. 302

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[1] Haghighat, F. and M. Chandrashekar. 1987. System-theoretic models for building thermal analysis, *ASME Journal of Solar Energy Engineering*, Vol. 109, pp. 79-88.

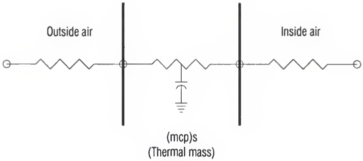

Figure 89: Electrical analogue of the thermal performance of a building element
Source: Burberry, 1983.[2]

Recent research and design applications have focused on physical modeling techniques and computer modeling. Computer model studies show the effect of different sizes of thermal mass, position and location of insulation and the effect of shading on thermal mass.

Simulated Model Setup

The layout shown below is a passive solar house because it uses (1) only passive cooling and heating techniques (thermal mass, shading, orientation, etc), (2) natural ventilation (through permanent vents in all openings), (3) natural daylighting (through glazed openings), and, (4) an east-west axis so that most windows face north and south. This assessment was made after a thorough study of the climate of Nairobi, Kenya.

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[2] Burberry, P. 1983. *Practical Thermal Design in Buildings*. London: Batsford Academic and Educational Limited.

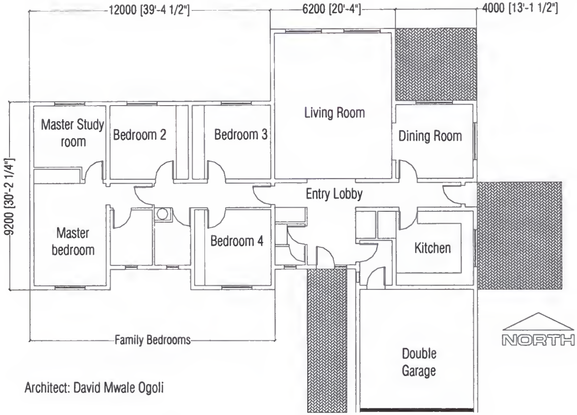
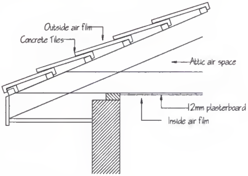
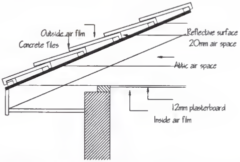
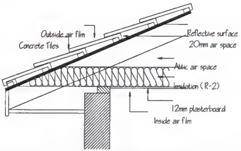


Figure 90: Plan of a passive solar house
Floor Area = 200m^2 (2153 ft^2)

The following comments in the Table below were made following parametric analysis regarding different types of construction. They were assessed based on different sizes of thermal mass located on external wall and internal partitions. The effectiveness of insulation in reducing energy load was tested.

The following layouts show some of the arrangements used to parametrically study the houses for the effect of insulation, shading and orientation on thermal mass. The analysis was done using *Energy-10 program* (Balcomb, 1996).

Table 14: Detail of roof construction

Roof Systems	U-value (SI units)	U-value (I-P units)	Impact on Energy usage
 Outside air film Concrete Tiles Attic air space 12mm plasterboard Inside air film Plain tile roof	2.398	0.422	Cool roofs generally imply less energy use at the equator (the sun is overhead most of the daytime). The attic space left unprotected is a source of large heat gains at the equator. About 30% of the cooling load is conducted through the ceiling.
 Outside air film Concrete Tiles Reflective surface 20mm air space Attic air space 12mm plasterboard Inside air film Plain tile roof with reflective surface	0.796	0.140	High thermal mass roofs made of tiles perform better when a radiant barrier is added. A ventilated attic space reduces the heat build-up, which in turn reduces the cooling load.
 Outside air film Concrete Tiles Reflective surface 20mm air space Attic air space Insulation (R-2) 12mm plasterboard Inside air film Plain tile roof with reflective surface and insulation	0.229	0.040	Insulation that is used in combination with thermal mass should extend over the top ceiling and allow ventilation at the eaves. Adversely cool or hot air should be impeded from getting to indoor spaces.

Note: The U-value (thermal transmittance) of the walls is generally larger than that of the roofs because the roof receives the highest portion of incident solar radiation. Materials that have high thermal transmittance allow more heat transfer. Conversely, materials of low thermal transmittance impede heat transfer. As a general rule, U-values for roofs ought to be a low as possible.

Table 15: Details of wall construction

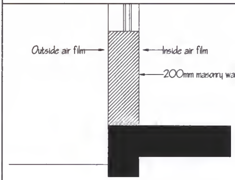
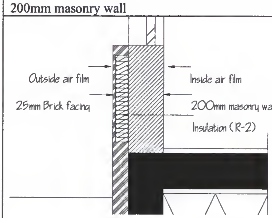
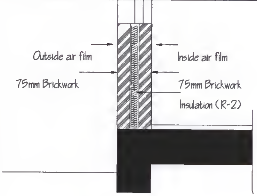
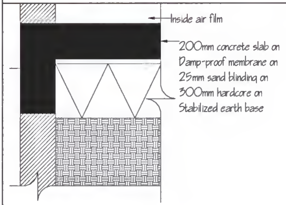
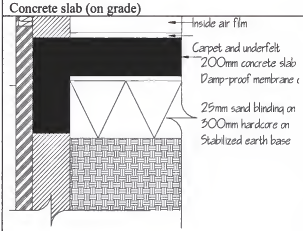
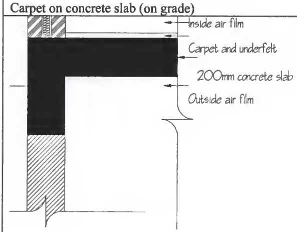
Wall Systems	U-value (SI units)	U-value (I-P units)	Impact on Energy usage
 200mm masonry wall	4.396	0.774	Common brick, natural stone and concrete blocks account for most permanent buildings in Kenya. Wood frame walls tend to have more air leaks than masonry walls. High thermal mass walls can absorb and store heat and prevent rapid temperature swings.
 Outside air film 25mm Brick facing Inside air film 200mm masonry wall Insulation (R-2) 200mm insulated masonry wall	0.429	0.075	Masonry walls with brick facing can have less insulation than the equivalent wood frame construction for the same amount of energy input. High thermal mass walls are effective at sizes ranging from 100mm (4") thick (optimum thickness is 200mm (8").
 Outside air film 75mm Brickwork Inside air film 75mm Brickwork Insulation (R-2) 200mm brick cavity insulated wall	0.461	0.081	Interior cavity in wall construction has minimal effect on energy usage. In fact, a light-coloured exterior surface reflects a lot of incident solar radiation and saves cooling energy. Insulation is more effective on the exterior side. Dark surfaces absorb 70-90% of incident solar radiation.

Table 16: Detail of floor construction

Floor Systems	U-value (SI units)	U-value (I-P units)	Impact on Energy usage
 Inside air film 200mm concrete slab on Damp-proof membrane on 25mm sand blinding on 300mm hardcore on Stabilized earth base Concrete slab (on grade)	2.569	0.452	Concrete slab floors need to be exposed to direct solar radiation through windows. This makes the high thermal mass to store daytime heat to keep occupants comfortable at night.
 Inside air film Carpet and underfelt 200mm concrete slab Damp-proof membrane 25mm sand blinding on 300mm hardcore on Stabilized earth base Carpet on concrete slab (on grade)	1.276	0.225	Slab-on-grade foundations reduce space-conditioning energy by about 15%. These cost savings derive from the fact that floors have high thermal mass and year-round deep earth temperature stays constant.
 Inside air film Carpet and underfelt 200mm concrete slab Outside air film Carpet on concrete slab (Suspended)	1.276	0.225	Slab-on-grade foundations were found to be more energy-efficient than raised (crawl space) foundation systems. The air below the floor varies a lot and increases conditioning energy.

Ranking of Energy-Efficient Strategies

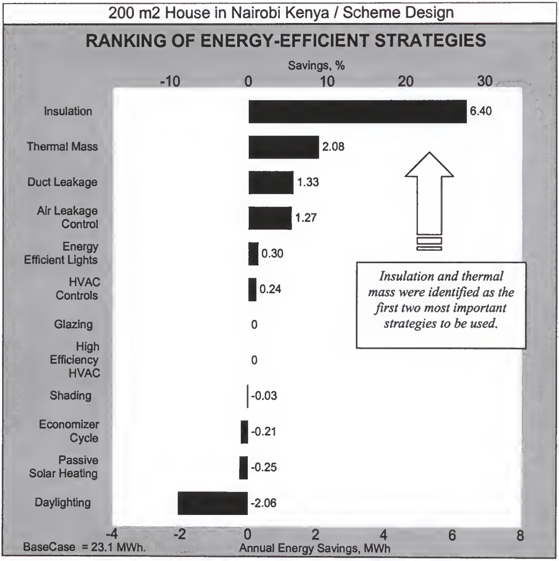


Figure 91: Ranking strategies BEFORE applying insulation and thermal mass

The figure illustrates a RANK done on the standard house.[3] Ten strategies were individually applied, simulated, and unapplied, and the savings compared. The use of high-efficiency HVAC systems was considered for comparison with passive solar systems. All windows were shaded.

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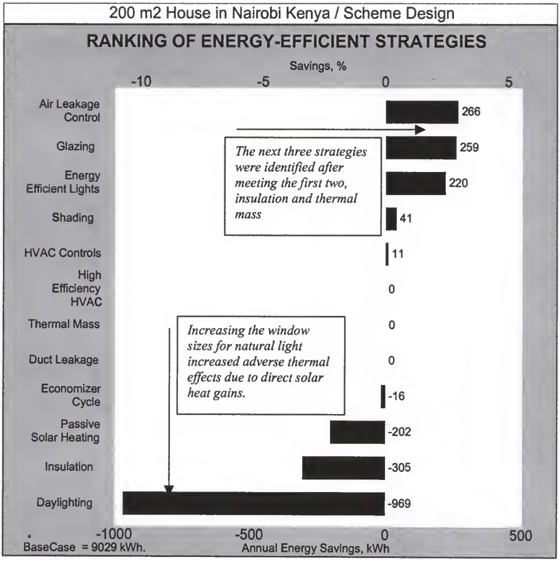
[3] A standard house is one made of common building materials without insulation. Walls were made of 100mm (4") thick concrete masonry units (CMU) with concrete roofs (R-30).



The next three strategies were identified after meeting the first two, insulation and thermal mass

Increasing the window sizes for natural light increased adverse thermal effects due to direct solar heat gains.

Figure 92: Ranking strategies AFTER applying insulation and thermal mass

The figure summarizes the effect of changes made when insulation and thermal mass were applied to create a more energy-efficient passive solar house. Thermal mass was in the form of 200mm (8") thick stonewalls, concrete tile roofs and thick floors close to window openings. At this point the size of windows should be adjusted to reconcile needs for view and natural daylight while avoiding adverse thermal conditions.

Simulated Results

Figure 93[4] shows a breakdown comparison of annual energy use, annual energy cost, monthly electric demand peaks for a standard house (Standard 1) and the energy-efficient house (Passive Solar Building) that utilizes high thermal mass. The electric bill includes items like plug loads and artificial lights.

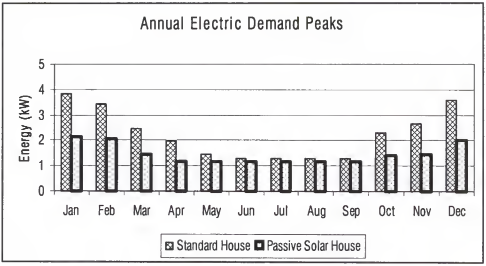


Figure 93: Monthly electric demand peaks

The highest monthly demand peaks occur between October and March, the hottest part of the year. The highest monthly demand is in January 3.83 kW (13,067 Btu/h) (Standard House) and 2.12 kW (7,233 Btu/h) (Passive Solar Building). The lower peaks occur between April and September, with values of 1.29 kW (4,401 Btu/h) (Passive Solar Building). The average monthly values are 2.24 kW (7,642 Btu/h) (Standard House) and 1.46 kW (4,981 Btu/h) (Passive Solar Building), which is a 35% reduction.

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[4] If this page is not in color, the values shown for each parameter on the graph for the Standard house are on the left-hand side and those for the Passive Solar House are on the right-hand side.

Figure 94 and 95[5] shows the annual energy use for the two houses. The results show that thermal mass can reduce annual energy for heating and cooling from 10.2 kWh/m^2, (3,300 Btu/ft^2) in the standard house to 3.0 kWh/m^2 (1,000 Btu/ft^2) in the passive solar house. This is a reduction of about 71% due to thermal mass only.

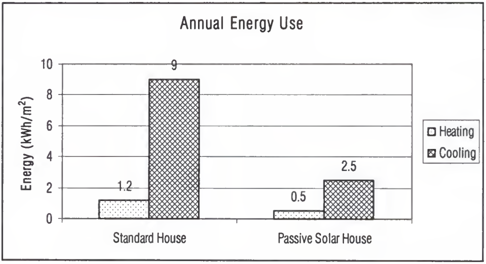

Figure 94: Annual energy use

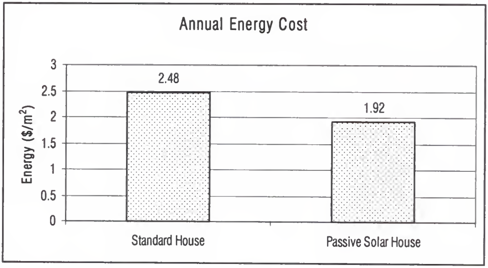

Figure 95: Annual energy cost

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[5] If this page is not in color, the values shown for each parameter on the graph for the Standard house are on the left-hand side and those for the Passive Solar House are on the right-hand side.

Figure 95 shows the annual energy cost. Energy for the standard house was 2.48 $\$/m^2$ (0.230 $\$/ft^2$) while that for the passive solar house was 1.92 $\$/m^2$ (0.179 $\$/ft^2$). This represented a cost reduction of 23%.[6]

Analysis and Discussion

This section shows a parametric analysis of the effects of different sizes of thermal mass, insulation levels and shading types. Simulation programs, like *Energy-10*, provide a means to study different types of arrangements before building a real building.

Effect of Shading in Different Orientations

Figure 96 shows the effect of annual energy use in the building due to shading in different orientations. It summarizes the amount of energy due the effect of orientation and shading of windows. When all the windows are unshaded the amount of energy used is 9.7 kWh/m^2 (3,138 Btu/ft^2) and when they are shaded the energy usage is 2.2 kWh/m^2 (712 Btu/ft^2) representing a reduction of 77%. In fact, shading east and west windows accounts for a reduction of energy load of 51%.

The figure shows the impact of shading by objectively showing the benefits of shading at the equator. East and west windows when shaded save 51% of the cooling energy. North and south windows may remain relatively unshaded but when fully shaded from direct solar radiation they account for a further 26% of the cooling energy.

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[6] The cost reduction for energy between the two houses is lower by 23% while the annual energy use is lower by 35%. This is because delivered or purchased energy is mainly used for lighting and not used for heating or cooling. Passive heating and cooling are the key methods for thermal regulation.

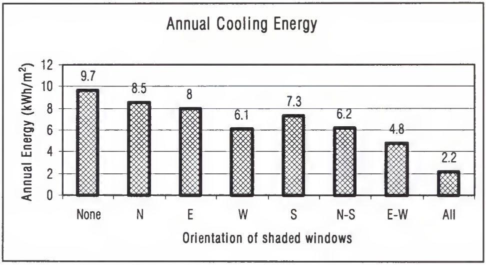


Figure 96: Annual cooling energy for different shading orientations

Effect of the Position of Insulation

The position of insulation is critical. Table 17 and Figure 97 show the effect of using insulation on the outside as opposed to the inside relative to the position of thermal mass. Insulation on the outside shows a reduction in energy use of about 19.6% below the levels of that one on the inside. Insulation on the outside has better energy performance than when it is placed on the inside of thermal mass.

Table 17: Effect of position of insulation on annual energy use

	Insulation on Outside (kWh/m^2)	*Insulation on Inside (kWh/m^2)*
Heating	0.7	1.2
Cooling	2.2	2.4
Total	2.9	3.6

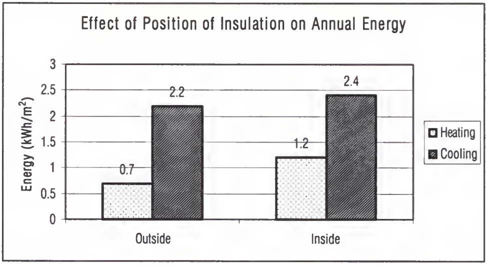
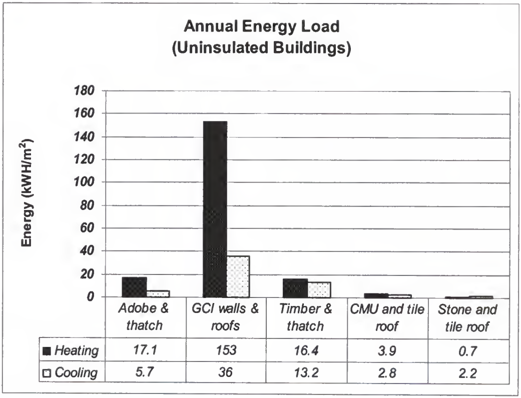


Figure 97: Effect of position of insulation on annual energy



	Adobe & thatch	GCI walls & roofs	Timber & thatch	CMU and tile roof	Stone and tile roof
■ Heating	17.1	153	16.4	3.9	0.7
□ Cooling	5.7	36	13.2	2.8	2.2

Figure 98: Energy consumption (kWh/m^2) for houses

Figure 98 shows a comparison of thermal performance of materials locally used. The houses require the less energy as thermal mass increases. Of the materials, GCI sheets lack thermal inertia that is necessary to reduce temperature swings. All the assemblies did not have insulation except stone/tile option that was used to gauge the impact of insulation beyond a standard CMU/tile house.

Comparison with Previous Studies

An extensive investigation of the effect of a window's orientation under various conditions of shading was conducted by Givoni at the Building Research Station of the Technion, in Haifa, Israel (Givoni, 1976, pp. 213-231).[7] An experiment was setup comprising four rotatable models of 1 x 1 x 1m with walls 150mm thick of lightweight concrete. One wall of the model had a window and the rear wall had a smaller opening with an insulated shutter-board. The four models had windows that could be shaded and were oriented in the four cardinal directions. Givoni (1998, pp. 65) noted following the findings:

1. Immediately at sunrise, as expected, showed a steep rise temperature.
2. The indoor maximum window in the model with the eastern window was about 6°C (11°F) above the outdoors' maximum.
3. In the western window model the indoor maximum temperature was 11°C (20°F) above the outdoor maximum temperature.
4. The models with unshaded southern and northern windows had roughly similar patterns, with much lower elevation of their indoor maximum temperature of about that of the outdoor.

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[7] Givoni, Baruch. 1976. *Man, Climate and Architecture*. London: Applied Science Publishers. Chapter 11: Orientation and its effect on indoor climate.

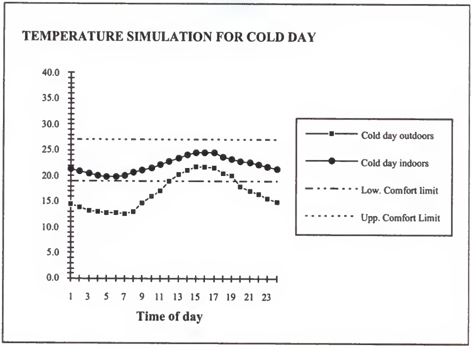
5. With effective shading, and with even low ventilation rate, the effect of the orientations of the windows almost disappeared.
6. With cross-ventilation, even when the windows are not shaded, the effect of the orientations of the windows of the windows disappeared.
7. The quantitative effect of the envelope color on the indoor air temperature, and on the energy demand of a building, depends on the thermal properties of the walls and the roof, as well as on the ventilation conditions (Givoni, 1998, pp. 78).

Building orientation affects the indoor climate by determining the effect of solar radiation and ventilation due to the prevailing winds. Thermal mass is the barrier that receives the impact of these conditions.

Simulated indoor temperatures

QUICK II is a thermal analysis program that can simulate the thermal performance and indoor comfort conditions in buildings. Mathews and Richards (1989, pp. 61-80) developed it at the University of Pretoria in South Africa. It can simulate hourly indoor temperatures in single zone although it does not offer temperature stratification in a room, interior surfaces are considered to be at the same temperature and it does not take into account wind effects (Balarus, 1996, pp. 5). *QUICK II* can predict the effect of a building area with the ground contact or a raised intermediate floor.

Figure 99 shows the simulated indoor temperatures in a building with high mass walls, 200mm (8) thick. Outdoor temperatures are also shown. It is clearly visible from the chart that thermal mass can maintain thermal comfort conditions indoors.



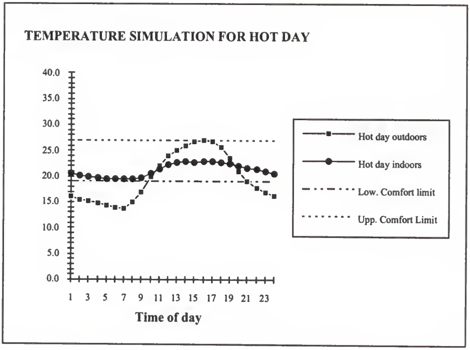


Figure 99: Simulated indoor temperatures for a building with walls 200mm thick

The "cold and hot" days are respective annual coolest day (July) and hottest day (February).

Conclusions

The two broad categories of buildings are those where people live and those where people work. Buildings where people work tends to require more lighting and less heating energy than buildings where people live. In buildings where people live about 80% of the energy is used for maintaining the temperature and lighting accounts for 0.5%. Natural ventilation should be used more for temperature control. There are benefits of shading windows at the equator. The following were observed:

1. Thermal mass can reduce annual heating and cooling energy by 71%.
2. All windows need to be shaded. East and west windows when shaded save 51% of the cooling energy. North and south windows may remain relatively unshaded but when fully shaded from direct solar radiation they account for a further 26% of the cooling energy.
3. Insulation on the outside shows a reduction in energy use of about 19.6% below the levels of that one on the inside. Insulation on the outside has better energy performance than when it is placed on the inside of thermal mass.

Building orientation affects the indoor climate by determining the effect of solar radiation and ventilation due to the prevailing winds. Thermal mass is the barrier that receives the impact of these conditions.

CHAPTER 7
CONCLUSIONS

Introduction

Architecture is a process[1] – from inception, through design development to completion. Basic design decisions have energy consequences. Energy is used to run and maintain buildings. Energy consumption in buildings is related to the local climate, building systems, occupancy patterns and the thermal properties of the building materials. Energy use is an important concern because it affects (1) the choice of building materials and methods (2) architectural form and layout planning (3) response to site and natural features. Some building materials waste energy while others, such as those where thermal mass is applicable, conserve cooling and heating energy. Not all energy issues can profoundly affect architectural form, but architectural form can profoundly affect energy use. Psychological expectations have a bearing on the use of energy in buildings.

Traditional architecture around the world developed on a paradigm of harmony with local climate. Contemporary architecture has shifted to a new different paradigm: "international style" that is based solely on technology without adapting design to local climate. Charles Jencks predicted that air conditioning would merge indoor and outdoor environments, day and night activities, summer and winter seasons, and north and south orientations. This is largely true now that human activity is a twenty-four hour cycle. However, some recent trends seem to indicate that dependence on mechanical systems ignores the local climate and passive strategies while being preoccupied with architectural form. These systems continue to contribute harmful gases, thus raising global concerns of ozone depletion and climate-change. Architecture is now a reflection of this industrialized society. Industrialization and increased standards of living cause rises in energy demand. In non-oil producing developing countries, this demand is increasingly becoming harder to cope up with. A solution is needed. This dissertation is focused on buildings with high thermal mass and energy use in passive solar buildings as means to reduce the use of nonrenewable energy in buildings.

Equatorial Climate is Unique

One of the major reasons why this study was adopted is because the equatorial highland climate has major points that are usually overlooked. Such items are translated into high-energy design strategies and costs to cover unnecessary mechanical systems. The degree-days of various locations at the equator differ dramatically with altitude (Figure 100). An equatorial highland region like Nairobi, Kenya, has a moderate climate.

To put into perspective, the climate of Nairobi (1.3°S) was compared with Tel Aviv (32°N), and Sede Boqer (31°N) in Israel and Los Angeles, California (34°N) in USA in below.[2] These cities were chosen for comparison with Nairobi because Baruch Givoni, a major reference throughout the study, conducted similar studies cited in these locations (Figure 101). The figure shows that increasing the distance from the equator increases degree-days. Consequently, building energy increases.

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[1] CEC: Commission of European Communities. 1990. *Passive solar energy as a fuel – 1990-2010*. Executive Summary, Commission of European Communities, DGXII, pp. 29.

[2] The studies by Givoni were mainly conducted in Tel Aviv, Israel and Los Angeles, California and were widely used for comparison in this dissertation.

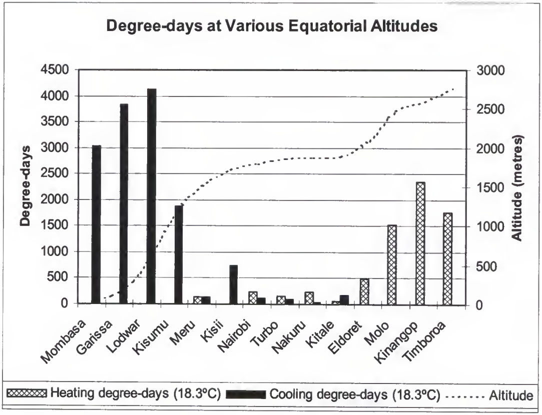

Figure 100: Degree-days at various equatorial altitudes

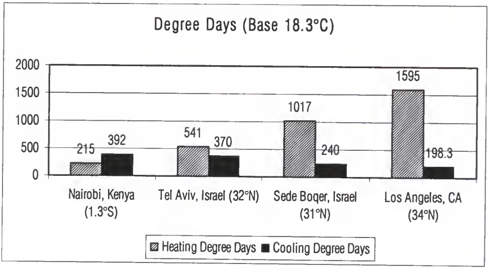

Figure 101: Annual degree-days for Nairobi, Tel Aviv, Sede Boqer and Los Angeles

Major Findings

Thermal capacity is closely related to mass. Insulation (as needed) must be between the mass and the outside air. Heavy materials have time lag and moderating effects to internal temperature conditions. A predictive formula for expected indoor maximum temperatures is:

$$\mathbf{T_{max\text{-}in} = T_{max\text{-}out} - 0.488 \times (T_{max\text{-}out} - T_{min\text{-}out}) + 2.44}$$

Where:

$T_{max\text{-}in}$ = Indoor maximum temperature;

$T_{max\text{-}out}$ = Outdoor maximum temperature

$T_{min\text{-}out}$ = Outdoor minimum temperature

The new equation was applied to the published work by Givoni and generated the results in Figure 33 (Chapter 2). The figure shows the measured data and computed data side by side with the results using the equations from Givoni and this study. The prediction of indoor maximum temperatures using the equation of Givoni are close although consistently higher than the measured values by about 2-3°C (4-6°F). It appears that there is good prediction using the new formula derived from this experimental research.

Figure 102 shows prediction of indoor mean radiant temperatures. The mean radiant temperature (MRT) in the high-mass building as a function of time of day (x) is shown on the figure. It also shows the prediction of floor temperatures. The equations established were:

$$\mathbf{MRT = -0.0034x^3 + 0.1433x^2 - 1.5553x + 27.321} \qquad (R^2 = 0.939)$$

$$\mathbf{Floor\ Temperature = -0.001x^3 + 0.047x^2 - 0.5798x + 24.953} \qquad (R^2 = 0.8561)$$

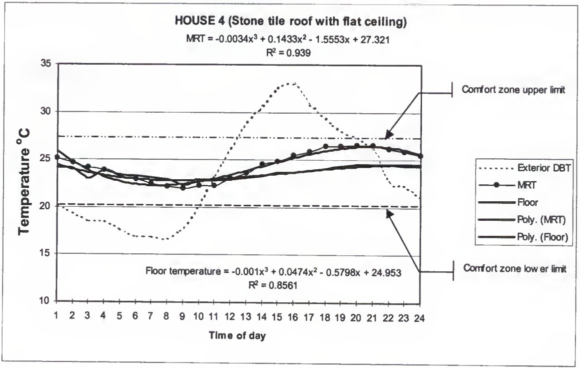

Figure 102: Predicted indoor mean radiant temperatures in high mass building

An analysis of mean radiant temperatures measured in low mass buildings in this study showed a strong correlation (r = 0.943) with exterior air temperature. The regression line of best fit is given by:

Mean Radiant Temperature = 0.837 (Exterior air temperature) + 5.365

The following relationships were also established:

Table 18: Mean radiant temperatures (MRT) Equations

No ceiling	$MRT = 1.89*T_{floor} - 17.30$
Slope ceiling	$\mathrm{MRT} = 1.30*\mathrm{T}_{\mathrm{floor}} - 5.42$
2/3 ceiling	$\mathrm{MRT} = 1.27*\mathrm{T}_{\mathrm{floor}} - 5.05$
Flat ceiling	$\mathrm{MRT} = 1.96*\mathrm{T}_{\mathrm{floor}} - 22.40$

Where $\mathrm{T}_{\mathrm{floor}}$ is the temperature of the floor.

The time lag for a 200mm thick heavy mass building material may be determined by an equation revised from the version published by Bansal *et al.* (1994, pp. 52) is:

$$\text{Time lag, } \phi = 0.73 \times s\sqrt{\frac{\rho \times c}{2 \times k \times \omega}} \text{ (Revised equation)}$$

Where:

s = thickness of the wall (m)

k = thermal conductivity (W/m K)

ρ = density of material (kg/m3)

c = specific heat capacity of material (J/kg K)

$$\omega = \frac{2 \times \pi}{24 \times 3600} (\text{s}^{-1})$$

Future Research

There are a number of subjects that have arisen from this study that require further experimental climate chamber studies and field research. The outline is stated here below.

Establish Thermal Comfort Standard

Thermal comfort needs further study. The parameters of conditions that most people consider to be comfortable need to be established. Two stages of this work should include climate chamber experiments and field studies in "normal" working environment. A recent study[3] presented an assessment method summarized in Figure 103 in which preventive and diagnostic aspects of work proposed further study might proceed.

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[3] Ogoli, David Mwale. 2000. An assessment method for the performance of passive solar buildings at equatorial high altitudes in *Architecture, City and Environment: Proceedings of PLEA 2000, Cambridge, UK (July 2000)* by Koen Steemers and Simos Yannas (eds) pp. 827-828. James & James (Science Publishers) Ltd.

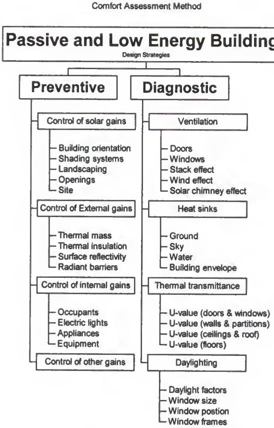

Figure 103: Design strategies for passive and low energy buildings

Seven Other Areas of Further Research

Other areas of further research will be to conduct experimental tests to establish:

1. Building and energy consumption in buildings
2. Thermal effects of insulation and thermal mass
3. Thermal effects of wall orientation and color
4. Time lag and decrement factors of various building materials
5. Natural Ventilation standard
6. Thermal effects of landscape in reducing ambient temperatures
7. Thermal effects of ground temperatures and use of buried pipes

APPENDIX A
APPENDIX A: DEFINITION OF TERMS

The term **thermal mass** is commonly used to signify the ability of materials to store significant amounts of thermal energy and delay heat transfer through a building component. This delay leads to a slower response time that tends to moderate indoor temperature fluctuations under outdoor temperature swings. Thermal mass can be used to move off-peak energy demand. High thermal mass materials have high densities such as natural stone (1500 kg/m3) and concrete (2240 kg/m3).

Passive cooling, heating and lighting systems are design methods that save energy by inexpensively putting the energy-control function in the building itself through active and passive systems. A passive solar building is one that integrates with the local climate. It uses natural ventilation, natural daylighting, solar heat gains, appropriate thermal mass, shading, windows (size, shape, location, framing, glazing type), building orientation, insulation, and slab-on-grade foundation. Passive solar systems require little, if any, nonrenewable energy to make them function.

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment (ASHRAE 1997, pp. 8.1). Comfort is not a physiological condition but a state of mind (Fontain, *et al.* 1996, pp. 179-182). Thermal comfort has been defined operationally as the range of climatic conditions considered comfortable and acceptable inside buildings (Givoni, 1998b, pp. 3). Comfort is a state of well-being or relief or a measure of human acceptability of the physical environment (UN, 1991, pp. 16).

Temperature is a measure of hotness or coldness. Ambient temperature is the temperature of the air surrounding the occupant and mean radiant temperature the temperature of an imaginary isothermal black enclosure in which an occupant would exchange the same amount of heat radiation as in the actual non-uniform environment.

In the article *Understanding what humidity does and why,* Elovitz[1] provides several definitions for different measures of humidity. They are adapted and adopted for this study:

> **Relative humidity** is the ratio of the amount of water vapor in the air to the amount of water vapor air can hold at that temperature. At 100% relative humidity, the dry bulb, wet bulb and dew point temperature are equal. At 100% relative humidity, the air is saturated, which means it cannot hold any more moisture.
>
> **Specific humidity** is the amount of moisture in the air per unit mass. Specific humidity is proportional to the enthalpy or total energy content of the moist air mixture.
>
> **Dew point** is the temperature where moisture begins to condense out of the air. When air is cooled to its dew point, it reaches 100% relative humidity or saturation.
>
> **Vapor pressure** is the pressure exerted by free molecules at the surface of a solid or liquid. For a given substance, vapor pressure is a function of temperature.

Raising the temperature without changing the amount of moisture in the air reduces the relative humidity. The relative humidity goes down because warmer air can hold more moisture than cold air. Specific humidity changes when moisture is added or removed. Changing temperature does not change specific humidity unless the air is cooled below the dew point. Cooling the air any further causes the water vapor in the air to change to the liquid phase. Liquid water molecules accumulate, droplets form, and moisture condenses out of the air. As temperature increases, vapor pressure increases. Vapor pressure is a measure of the affinity of a substance for itself. If a substance has low affinity for itself, it evaporates readily even at low temperature. The substance will have a high vapor pressure.

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[1] Elovitz, Kenneth M. 1999. Understanding what humidity does and why. *ASHRAE Journal* April 1999, pp. 84-90.

Equatorial regions are tropical areas between latitude 10° N and 10° S. High altitude areas are considered places that are above 915m (3000 feet) above sea level.[2] These regions are generally categorized with high solar angles and usually experience a two-season annual climatic cycle.

Energy is the capacity to do work. The use of concentrated energy (fuels), rather than muscle power, is an important determining factor in industrial development. The supply and use of energy has implications on many other human activities. Efficiency increases the positive effect of energy. The following definitions are noteworthy:

> **Energy efficiency** is the capacity to produce results with a minimum expenditure of energy inputs. Waste energy is any energy in a system that is not directly serving the system's functions. A system is thought of as energy-efficient if its requirements are low in relation to the results produced, and if energy is not wasted.[3]
>
> **Energy-efficient design** embraces the design and building process, the building as it is to be used, and the building as it is actually used. Energy efficient design therefore prioritizes energy efficiency for human factors, the environment, economics, architecture, building elements, solar applications and monitoring.[4]

The Table below gives some of the parameters that describe thermal mass effects.

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[2] Ojany, F. F. and R. B. Ogendo. 1985. *Kenya: A study of physical and human geography*. Nairobi: Longman Kenya Limited pp. 38.

[3] ECE: Economic Commission for Europe, Geneva. 1991. *Energy efficient design: a guide to energy efficiency and solar applications in building design*. ECE Energy series No. 9. New York: United Nations p6. This document was written as a United Nations Development Programme (UNDP) project. The purpose was to enhance the professional skills of practicing architects, engineers and town planners to design efficient buildings which reduce energy consumption and make greater use of passive solar heating and natural cooling techniques, pp. 6.

Table 19: Parameters for describing thermal mass effects

Parameter	Physical meaning	Reference
Admittance factor	Represents the extent to which heat enters the surface of materials in a 24-hour period cycle of temperature variation	Burberry 1983
Capacitance	Accounts for the ability of the external and internal materials to store heat	Shaviv & Shaviv 1978
CLTD	Includes the effect of time lag in the propagation of heat through the material, due to thermal storage	ASHRAE 1997
Diurnal heat capacity	Measures the effectiveness of a material for heat storage during a continuous 24-hour period	Balcomb 1983
Effective heat capacity	Accounts for the effects of the building materials' thermal properties and design factors on the long term energy performance	Givoni 1987 & 1998b
Heat capacity	Introduces the effect of heat storage for different building types in the correlation coefficients used in calculating the solar saving fraction	Givoni 1987 & 1998b
Solar saving fraction	Correlation coefficients as a function of the heat capacity for specific building types	Givoni 1987 Stein 2000
Thermal capacity	Determines the heat flow in unit time by conduction through unit thickness of unit area material, across a unit temperature gradient, defined as the product of density by specific heat.	ASHRAE 1997
Total thermal time constant	The heat stored in a whole enclosure per unit of heat transmitted to or from the outside through the elements surrounding the enclosure and by ventilation	Givoni 1976

Source: Santamouris *et al.* 1996, pp. 203[5]

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[4] Ibid. pp. 7.

[5] Santamouris, M. and D. Asimakopolous (ed). 1996. *Passive Cooling of Buildings.* London: James & James (Science Publishers) Ltd. pp. 203

APPENDIX B

APPENDIX B: TEMPERATURES IN EXPERIMENTAL HOUSES

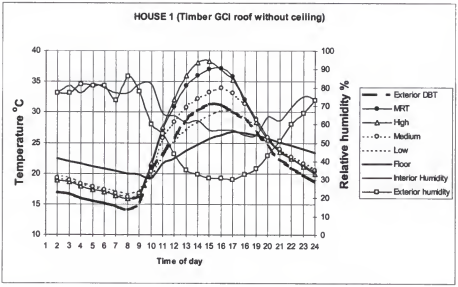


Figure 104: Outdoor and indoor temperature patterns in the timber houses

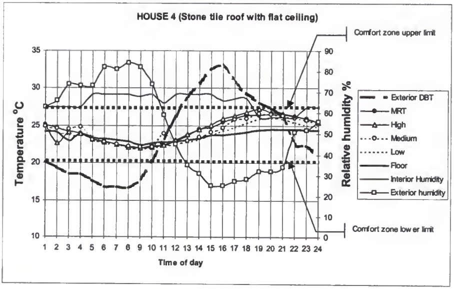


Figure 105: Outdoor and indoor temperature patterns in the stone houses

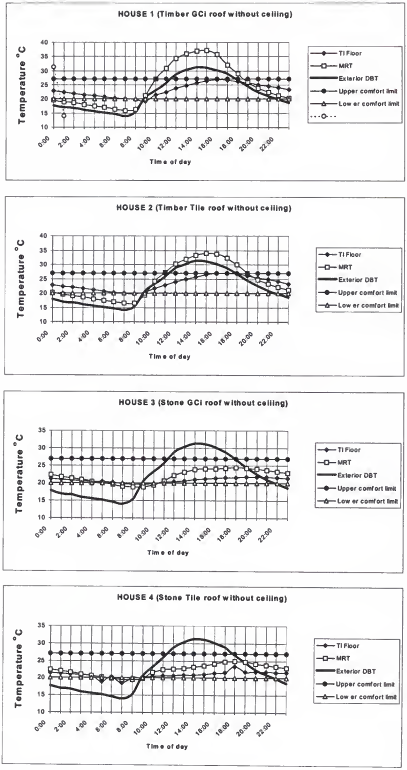


Figure 106: Mean radiant temperatures within all houses (without ceiling)

APPENDIX C
APPENDIX C: STATISTICAL RESULTS

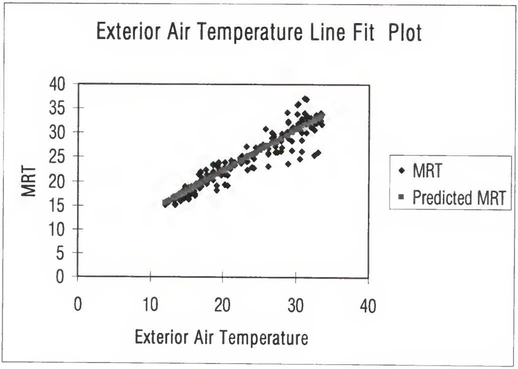
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.943305
R Square	0.889825
Adjusted R Square	0.889245
Standard Error	1.858131
Observations	192

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	5298.203	5298.203	1534.532	6.09E-93
Residual	190	656.0036	3.45265		
Total	191	5954.207			

	Coefficients	*tandard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*Ipper 95.0%*
Intercept	5.364786	0.498145	10.76952	2.04E-21	4.38218	6.347393	4.38218	6.347393
Exterior Air Temper	0.837246	0.021373	39.17311	6.09E-93	0.795087	0.879404	0.795087	0.879404



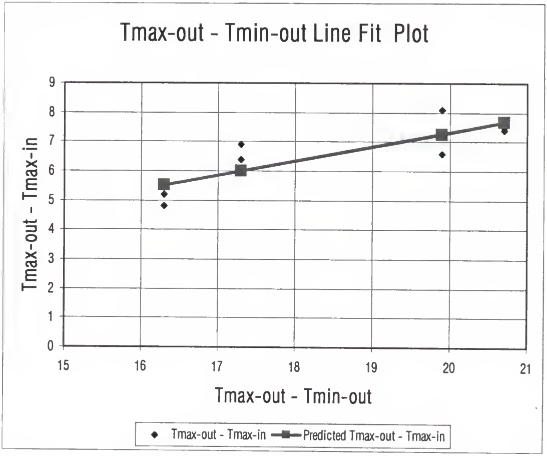
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.83026
R Square	0.689331
Adjusted R Square	0.637553
Standard Error	0.683734
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	6.223796	6.223796	13.31315	0.010723
Residual	6	2.804954	0.467492		
Total	7	9.02875			

	Coefficients	*tandard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	-2.438963	2.492474	-0.978531	0.365602	-8.537832	3.659905	-8.537832	3.659905
Tmax-out - Tmin-ou	0.48795	0.133732	3.648719	0.010723	0.16072	0.815179	0.16072	0.815179



APPENDIX D
APPENDIX D: SOLAR CHARTS

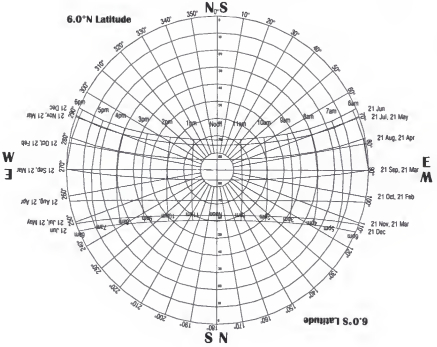


Figure 107: Sun path diagram at the Equator (0º N/S)

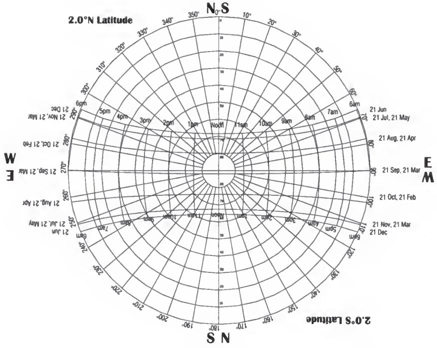


Figure 108: Sun path diagram at latitude 2° N

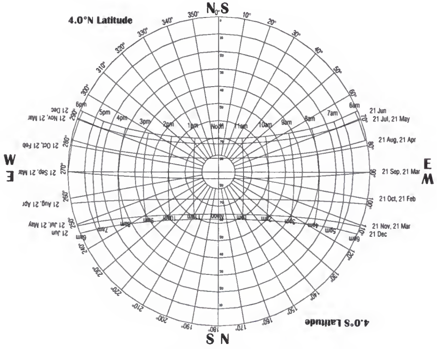


Figure 109: Sun path diagram at latitude 4° N

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BIOGRAPHICAL SKETCH

David Mwale Ogoli was born in Kaimosi in Vihiga District, Kenya, on 9th October 1962. He was born fifth in a family of nine energetic children who offered a challenging academic and social environment in the early days at Kaimosi. He pursued Ordinary-level studies at Sigalagala Secondary Technical School near Kakamega and Advanced-level studies at The Mombasa Polytechnic in Mombasa, Kenya.

He attended the University of Nairobi and graduated at the top of his class with the degree of Bachelor of Architecture (First Class Honors) in June 1988. He was awarded a British Chevening Scholarship to attend the University of Cambridge, UK, and graduated with a Master of Philosophy degree in November 1994. He was awarded a J. J. Fulbright Scholarship to attend the University of Florida, USA, where he graduated with a Doctor of Philosophy degree in December 2000. He received several awards including the University of Florida's ARCC King Student Medal for Excellence in Architectural and Environmental Design Research, and he won the First Prize for the Witter's Competition 2000. He was mentioned in the Jury's report of the Zephyr Competition conducted by the European Commission in 1994.

He worked with several architectural firms in Kenya and became a Registered Architect in 1990. In 1992, he was appointed as a Lecturer at Jomo Kenyatta University of Agriculture and Technology (JKUAT) in Nairobi, Kenya. He has deep interest in Building Science (Environmental Technology) and Energy issues in Architecture.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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